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DESIGN OF A SUPPLY CHAIN NETWORK WITH FINANCIAL CONSIDERATIONS

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Thesis

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Biographical note

Alexandra Borges is a lecturer at Polytechnic Institute of Viana do Castelo (IPVC) since 2001, in the area of Logistics and Operations Management. She started her professional career in the automotive business sector (BMW PT) in 1996, where she remained until 2012, developing professional experience in the marketing/commercial and quality/operations management areas. In 2012 she got a title of specialist in Management and Administration (area of quality management) awarded by IPVC, Instituto Politécnico de Bragança (IPB) and IPP (Instituto Politécnico do Porto) through the provision of public evidence. She has a degree in Management from the Faculty of Economics, University of Porto and a master graduation in Business Operations Management from the Catholic University of Porto. She is now a candidate to conclude the Doctoral Program in Business and Management Studies in the Faculty of Economics of Porto.

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Abstract

In the past few years, important supply chain decisions have captured managerial interest. One of these decisions is the design of the supply chain network incorporating financial considerations, based on the idea that the establishment of new facilities and the operating costs have a direct effect on the company's financial performance. However, works on supply chain network design (SCND) incorporating financial decisions are scarce. In this work, we propose a mixed integer linear programming (MILP) model to address a SCND problem where combined operational and investment decisions maximize the company value, measured by Shareholder Value Analysis (SVA), while respecting the usual operational constraints, as well as financial ratios and constraints. In particular, our model considers the design of a deterministic multiproduct, multi-echelon supply chain network (SCN) problem in a dynamic environment, allowing for decision making at every single time period of the planning horizon, in order to deal with market fluctuations. The model is tested using a case study available in the literature and is solved using the mathematical programming solver Gurobi 7.0.1.

This work extends current research by introducing infrastructure dynamics, and adding the possibility of closing facilities. It also improves financial aspects when modelling a SCN by considering debt repayments and shareholders capital entries as decision variables, as well as improving on the calculation of some financial values; which together lead to greater value creation. Finally, measuring the value created by using SVA is also an improvement to current research not only because it is the most supported approach in the literature, but also because it avoids some of the drawbacks of Economic Value Added (EVA), such as increasing inventories (which increases production) in order to increase the value of the company.

Resumo

Nos últimos anos, decisões importantes sobre a cadeia de abastecimento captaram o interesse dos gestores. Uma dessas decisões é a configuração / reconfiguração da rede da cadeia de abastecimento incorporando considerações financeiras, com base no facto de o investimento necessário para estabelecer novas instalações e os custos operacionais resultantes afetarem diretamente o desempenho financeiro da empresa. No entanto, trabalhos sobre a configuração da cadeia de abastecimento que incorporem decisões financeiras são escassos. Nesta tese, propomos um modelo de programação linear inteira mista para resolver um problema de configuração de uma cadeia de abastecimento, que inclui as decisões operacionais usuais, mas também decisões de investimento e tem por objetivo a maximização do valor da empresa, medido por *Shareholder Value Analysis* (SVA). Para além das restrições operacionais usuais, também se impõem restrições que permitam cumprir diversos indicadores e rácios financeiros. Em particular, o nosso modelo considera a configuração / reconfiguração de um problema determinístico de rede de cadeia de abastecimento de múltiplos produtos e níveis, em ambiente dinâmico, permitindo a tomada de decisões em todos os períodos do horizonte de planeamento, de forma a poder reagir às flutuações do mercado de forma eficaz e eficiente. O modelo é resolvido recorrendo ao Gurobi 7.0.1 e testado num estudo de caso disponível na literatura.

Este trabalho é inovador e contribui para a literatura em quatro vertentes. Por um lado, para além de permitir a abertura de instalações, também permite o seu fecho. Por outro lado, tais decisões são tomadas num ambiente dinâmico, ou seja, as decisões quanto à configuração da rede da cadeia de abastecimento são tomadas em cada um dos períodos do horizonte de planeamento. Relativamente aos aspetos financeiros há duas contribuições distintas. Uma relativa à inclusão de decisões financeiras, que nos trabalhos anteriores não eram consideradas, e outra relativa à função objetivo utilizada. A utilização do SVA como medida do valor da empresa, para além de ser a abordagem mais suportada na literatura, evita as desvantagens da utilização *Economic Value Added* (EVA), que incentiva a criação de inventários (e, consequentemente, da produção) como forma de aumentar o valor da empresa. Adicionalmente, é melhorado o cálculo de alguns valores financeiros, tais como depreciações, fluxos de caixa e amortização da dívida.

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1 Introduction

1.1 Introduction to supply chain management

One of the most significant changes in the paradigm of modern business management is the entering in a new era where individual firm performance and competitive advantage are linked to supply chain performance (Lambert et al., 1998). A supply chain consists of a set of companies directly involved in the upstream and/or downstream flows of products or services from a supplier to a customer (Mentzer et al., 2001). The main objective of supply chain management (SCM) is to maximize competitiveness and profitability of the company, as well as the whole supply chain network, as it offers the opportunity to capture the synergy of intra and inter-company integration and management (Lambert et al., 1998).

Until recently, strategic planning exercises in many companies were based on qualitative managerial judgments about future directions of the firm and the markets in which they compete, often ignoring supply chain. In the past few years, however, important supply chain decisions have captured managerial interest (Shapiro, 2004). Several developments, such as new technologies and short-life products, as well as fierce competition among companies and increasing expectations of customers have led organizations to make large investments in their supply chains (Govindan et al., 2017). In addition, the growth of globalization in the last couple of decades, along with its management challenges, has motivated both practitioner and academic interest in global supply chain management (Meixell and Gargeya, 2005; Govindan et al., 2017).

One of the greatest challenges in supply chain management is the design of the supply chain network of a company or of a set of collaborating companies. Supply chain network design (SCND) involves decision making at both strategic and tactical levels. The former addresses decisions regarding the number, location, and capacity of the facilities and the assignment of each market region to one or more facilities locations; while the latter addresses decisions regarding production (product mix and production quantities at each plant), inventory (which products are stocked at each facility and in which quantities), distribution (product flows), and transportation modes (Melo et al., 2009; Meixell and Gargeya, 2005; Klibi et al., 2010).

The strategic decisions are made for a long planning horizon (Klibi et al., 2010) and are considered one of the most important stages of supply chain management as it affects all the future tactical and operational decisions (such as production and transportation scheduling or vehicle routing) of the chain (Farahani et al., 2014). Therefore, to achieve important cost savings, they should be addressed simultaneously, when optimizing the supply chain network (Shen, 2007).

Moreover, companies operate in growing demand uncertainty environments, due the globalization of economic activities together with fast developments in information technologies, which have led to shorter product life cycles, smaller lot sizes and a very dynamic customer behaviour in terms of preferences (Melo et al., 2009). Such complexity leads to a great economic potential and practical need to optimally designing all activities of all supply chain entities (Garcia and You, 2015). As a result, a growing interest in sophisticated optimization models and tools has been observed in recent years both by practitioners and by academics (Melo et al., 2009; Papageorgiou, 2009; Grossmann, 2005; Barbosa-Póvoa, 2012; Chopra and Meindl, 2012).

1.2 The need for financial considerations

Besides the analysis of decisions affecting supply chain, researchers have mentioned the importance of financial considerations in the SCM context (Applequist et al., 2000; Shapiro, 2004; Meixell and Gargeya, 2005; Shah, 2005; Hammami et al., 2008; Puigjaner and Guillén, 2008; Melo et al., 2009; Papageorgiou, 2009; Longinidis and Georgiadis, 2011; Ramezani et al., 2014). Shapiro (2004) suggests that strategic planning in the firm should include analysis of corporate financial decisions when modelling a supply chain. For example, each year projected profits before interest and taxes, which are heavily dependent on supply chain and demand management decisions, are critical inputs to financial planning exercises. Conversely, corporate financial decisions regarding the expansion of the company (e.g. acquisition of companies with complementary product lines) are critical to the projected competitiveness of the firm's supply chain. Elgazzar et al. (2012) argue that managers should be aware of the connection between supply chain performance and the financial strategy of the company and how their operational actions can impact the overall financial performance, stating that the larger part of expenditures of the companies are related with supply chain activities. This view was already supported by Christopher and Ryals (1999). According to the authors, the drivers for value creation are revenue growth, operating cost reduction, fixed capital efficiency, and working capital efficiency; all of them are both directly and indirectly affected by supply chain management.

However, optimization models for corporate financial planning that merge with optimization models for supply chain planning are still scarce. Many authors (e.g., Shapiro, 2004; Ramezani et al., 2014; Mohammadi et al., 2017) state that most of the studies have ignored decisions involving revenues, uncertainties, investment planning and other corporate financial decisions, and many other aspects of enterprise planning that interact with supply chain planning. Our literature review allowed us to find two different lines of research in this subject. One, although innovative because it considers financial aspects as endogenous variables which model the financial operation and are optimized along with the other SCND variables, is too much focused on scheduling and planning problems of batch process industries. In the other, financial aspects are merely considered as known parameters used in constraints and in the objective function. We only found three studies (Longinidis and Georgiadis, 2011; Ramezani et al., 2014; Mohammadi et al., 2017) out of these lines of research, that explore the integration of operational decisions with financial decisions when planning the supply chain. However, comparing these three studies with our work, we innovate by using a new objective function (shareholder value analysis), by making decisions in a dynamic environment, and by including the possibility of closing facilities at any time period of the planning horizon. Furthermore, Longinidis and Georgiadis (2011) work uses too many assumptions which are far from realistic; Ramezani et al. (2014) study is single product; and Mohammadi et al. (2017) is focused on modelling the financial statement of the company disregarding operational decisions.

1.3 Scope of the thesis

Given the growing interest of both practitioners and academics in global supply chain management, and the connection between supply chain performance and the financial strategy of the company, there is a need to develop supportive decision tools, to help managers making decisions in order to improve the overall performance of the company.

In this context, the main purpose of this work is to integrate financial aspects in supply chain network design (SCND) in a decision-making model, ensuring the company sustainability and growth. Therefore, we address a deterministic multiple-period, multi-echelon, and multi-product problem that considers simultaneously operations and financial decisions. To solve this problem we develop a mixed integer linear programming (MILP) model, which extends that of Longinidis and Georgiadis (2011). At the strategic level our model determines number and location of facilities (plants, warehouses, and distribution centers), along with the links among them. At the tactical level, our model decides the quantities to produce and to store at each facility and to make them available at each customer zone, ensuring satisfaction of demand. As financial decisions, our model chooses the amount to invest, the source of the money needed to make this investment (cash, bank debt, or capital entries from shareholders) and the repayments policy to the bank. The objective function is the maximization of the value of the company through shareholder value analysis (SVA). SVA computes shareholder value (or equity value) by deducting the value of the long term liabilities at the end of the lifetime of the project from the value of the firm for the planning horizon in analysis, which is obtained through de discounted free cash flow (DFCF) method. Regarding the constrains, in addition to the usual operational constrains, we also consider minimum and/or maximum threshold values for performance ratios, efficiency ratios, liquidity ratios, and leverage ratios, in order to ensure the financial health of the company, while making supply chain strategic and tactical decisions. The problem is formulated as a MILP and is solved using the mathematical programming solver Gurobi 7.0.1. A receding horizon strategy can be used to account for environment dynamics of uncertainty, since such a strategy encompasses the implementation of the model decisions only in the short period, while solving the problem for a longer period. By repeatedly doing so, one can adapt its network to the reality being faced at any time.

By addressing the above issues, this thesis will improve current literature models in several ways. We will use shareholder value analysis to calculate shareholder value creation, which is the most supported approach in the literature. Moreover, our model is adaptive in nature and is capable of dealing with market dynamics, up to a certain extent, since it allows changing the infrastructure during the planning horizon, rather than just setting it at the beginning. These strategic decisions include not only the number and location of facilities to be opened but also the possibility of closing any facility during the planning horizon. It also allows making decisions for three echelons of the supply chain (plants, warehouses, and distribution centers). In addition, it considers accounting rules to calculate financial statement, balance sheet and financial ratios.

Part of this work, considering debt repayments and new capital entries as decision variables, improving on the calculation of some financial values, as well as introducing infrastructure dynamics while maximizing EVA, was already published as a book chapter (see Borges et al., 2019).

1.4 Thesis overview

The remaining chapters of this thesis are organized as follows:

Chapter 2 provides a literature review of supply chain management and all the decisions concerned with planning its structure. Then we review the main studies modelling supply chain and continue with a review of models with financial considerations, highlighting the importance of joint operational and financial decisions. Finally, we present the future trends in supply chain modelling.

Chapter 3 describes the problem that we address and the solution approach. The problem considers the design of a deterministic multiproduct, multi-echelon supply chain network, in a dynamic environment, regarding the production and distribution, as well as the infrastructure. Thus, allowing for decision making at every single period of the planning horizon. The problem is formulated as a MILP and is solved with the commercial software Gurobi Optimizer 7.0.1.

Chapter 4 describes the mathematical formulation of the problem. The proposed MILP uses shareholder value analysis as objective function and two groups of constraints: operational constraints (functional and logical) for the three echelons considered and financial constraints to ensure that financial ratios are in accordance with the bounds established, in order to maintain the financial health of the company.

Chapter 5 tests the validity of our model using the case study from Longinidis and Georgiadis (2011). We have performed two sets of experiments: on the one hand, used the objective function of the original work, which is the maximization of the economic value added (EVA); on the other hand, we used our proposed objective function, which is the maximization of shareholder value (SVA). In order to understand which aspects of our model improve the original work the most, we made several tests in each set of experiments. The results are reported and compared with the original work.

Finally, Chapter 6 draws some conclusions, explains limitations and points out future research directions. We conclude for the benefits of our model: on the one hand, the operational and financial decisions obtained allow creating more value for the company and, on the other hand, it is a model with less assumptions and thus, much closer to reality.

2 Literature review

2.1 From logistics to supply chain management

The logistics concept, first known as physical distribution, has undergone many significant changes over the past decades. As a cross disciplinary field, it is informed by a wide range of established disciplines like economics, mathematics, and engineering, each having its own perspective and methods, which lead the first logisticians to bring to the area the perspectives and methods from the fields and institutions where they came from (Klaus, 2009). The overall body of knowledge began in the late 1950s and early 1960s, despite the fact that a few authors started talking earlier about the benefits of getting the right goods to the right place at the right time. In the mid-1960s and until the mid-1980s it entered a new phase, which allowed the development and relative maturity of the discipline. From the late 1980s to the early 1990s, logistics entered a new era, called supply chain management.

2.1.1 First essays

The concept of trading off transportation and inventory costs was recognized formally at least as early as the mid-1880's, when Jules Dupuit, a French engineer wrote about the selection between road and water transport, and that exploitation of this basic trade-off goes even farther back in time (Langley, 1986). In academic literature physical distribution first appeared in the early 1900s and until the 1940's agricultural economics had a great deal of influence, since the attention was centred on transporting products from farms to markets (Kent and Flint, 1997).

From 1940 through the late 1950s, logistics embraced both business and military sectors. The military requirements of the World War II developed concepts such as transport engineering and efficient physical distribution (Kent and Flint, 1997). In the business sector, academic writings started only after the end of the war and, by that time, physical distribution was seen as a subset of marketing. Warehousing, wholesaling, inventory control, materials handling and inbound and outbound transportation were separate functions (Kent and Flint, 1997). These activities were not coordinated within the firm; they were very fragmented, because areas like marketing, production, and finance were thought to be more important (Langley, 1986; Ballou 2007).

2.1.2 The emergence of a new discipline

The late 1950's and early 1960's were the beginning of physical distribution as an area of study and practice. A study of the airline industry from 1956 made by Lewis et al. (*in* Kent and Flint, 1997) introduced the concept of total cost analysis to logistics and played a very important role in laying the foundations for physical distribution. Bowersox (1983) called the period from 1950 to 1964 the "Origination and a new direction". He explains that after the war world economy was growing, production was being expanded and the fast product proliferation needed to be supported by new distribution channels. However, he points out that the diffusion of the sales points and the need for more field inventories and warehouses reduced the distribution efficiency, substantially raising distribution costs. This led some companies to create a unit to manage physical distribution, with control over warehousing and transportation, but with no direct responsibility for inventory (Bowersox, 1983). Also in the early 1960,'s Peter Drucker raised the problem and focused attention on the challenges and opportunities in the field of logistics and distribution (Langley, 1983). The recognition of the high logistic costs led Drucker declare physical distribution as one of the most promising areas of business (Ballou, 2007). With marketing and production being relatively mature areas of analysis, logistics was an obvious area of attention (Ballou, 2007). The first logistics college course and textbook also appeared around 1960 (Ballou, 2007), but research was primarily descriptive and exhortative (Klaus, 2009).

The appearance of the systems concept integrated various outbound logistics functions into physical distribution, shifting the focus of physical distribution to an entire system of activities, called "integrated logistics" (Kent and Flint, 1997). The scope of physical distribution was extended to include physical supply and was called business logistics (Kent and Flint, 1997; Ballou, 2007).

Neither purchasing nor production was yet considered to be part of logistics and whereas purchasing was initially considered a buying activity, there were efforts to expand the scope to include many of the activities familiar to physical distribution but associated with the inbound side of the firm, calling them procurement or materials management (Ballou, 2007).

2.1.3 Creating maturity

In the early 1970s, the customer was regarded as the primary focus of the firm and customer service became a significant issue (Langley, 1986; Kent and Flint, 1997). By this time, marketing and production were established functions within business and they both embraced physical distribution, but their lack of attention to these activities led physical distribution to be developed as a separate function in a firm (Ballou, 2007).

The period from 1965 to 1979 was called by Bowersox (1983) "Physical distribution and materials management maturity". Throughout the world, business began to experience a series of economic downturns and the corporations moved from a purely cost-to-cost orientation to one that included revenue analysis (Bowersox, 1983). Physical distribution managers began to analyse marketing programs and planned customer service as well as to participate in inventory decisions and the materials management concept emerged, becoming proactive in planning strategies rather than reactive to reduce costs (Bowersox, 1983). The physical distribution structure expanded its span of control to include order processing, customer service, finished goods inventory as well as transportation and warehousing, and was commonly headed by top-level executives (Bowersox, 1983).

The role of operations research started in the late 1960s, due to the new possibilities of running large-scale models and mathematical calculations on computers along with a recognized need for truly scientific analysis and the growing operations research popularity (Klaus, 2009). One line of research focused on geographical aspects of logistical systems design and optimization, industrial location decisions, new approaches to vehicle routing, and scheduling and transportation optimization; another line of research focused on inventory levels, lot sizing and scheduling in production and distribution (Klaus, 2009). On those early years, scholars and practitioners could not agree on a title for the field. Some of the most commonly used are distribution, physical distribution, logistics, business logistics, integrated logistics, materials management, value chains, and rhocrematics (a greek term referring to materials flow management) (Ballou, 2007).

From the 1970s and 1980s, when third party logistics organizations concentrated and professionalized, the concept of industrialization of services, rooted in the field of scientific management, was gradually being discovered (Klaus, 2009). Another line of research that came up in parallel was the engineering instrumentation that started through engineers who specialized on research and development of hard equipment and systems for logistics operations such as mechanized and automated transport warehousing and packaging (Klaus, 2009). Latter, this work expanded to industrial materials flow equipment, container hardware systems, integration of technologies, computer-assisted planning, controlling, among others (Klaus, 2009).

After deregulation of transportation in the late 1970s and early 1980s, there was a strong economic incentive to coordinate inbound and outbound product movements within the manufacturing operations and purchasing activities were added to the scope of logistics management (Ballou et al., 2000).

In addition to legal changes, there were advances in information technology, extended product-flow channels brought about by the international and global operations of many firms, and increased customer demands for customized products and services with quick delivery response forced by high levels of competition (Ballou et al., 2000). These have encouraged managers to define their strategies in terms of product-flow channels that by then encompass multiple enterprises of suppliers, customers, and carriers (Ballou et al., 2000).

In the early 1980s, logistics started to play a key role as a differentiator for the firm and the concept of "supply chain management" emerged (Kent and Flint, 1997). The concepts of inter organizational efficiency, environmental logistics, reverse logistics also emerged along with the awareness of the importance of globalization (Kent and Flint, 1997). Logistics became a key input to strategy formulation in the area of market segmentation and, for some industries, logistics activities became their main competitive advantage (Langley, 1986).

2.1.4 Supply chain management

Supply Chain Management (SCM) is a discipline with several influences from logistics and transportation, operations management, materials and distribution management, marketing, as well as purchasing and information technology (Giunipero et al., 2008). The name "supply chain management" was first used by Keith Oliver, a senior vice president in Booz Allen, in 1982 (Laseter and Oliver, 2003). Oliver developed an integrated inventory management process to balance trade-offs between the customers' desired inventory and customer service goals. The original focus was in managing the supply chain as a single entity and not as a group of distinct functions, with the goal of fixing the suboptimal deployment of inventory and capacity caused by conflicts between functional groups within the company (Laseter and Oliver, 2003).

The early definitions, in 1990s, focused on the supply chain as a concept that covered the flow of goods, and management of relationships from suppliers to the ultimate customer (Giunipero et al., 2008). However, the definition of SCM as led to great discussions (Giunipero et al., 2008) and the diffusion of the field of supply chain management did not take place until the late 1990s, with most of the theoretical and empirical investigation commencing in 1997 (Lambert et al., 1998). Exactly what is SCM is still being debated: while some say it is a new concept, others say that it is a fulfilment of the activity integration promise implied in logistics early definitions, recognizing that the logistics pioneers had many of the ideas promoted by current supply chain enthusiasts (Ballou, 2007).

In 1998, the Council of Logistics Management, now named Council of SCM Professionals (CSCMP) modified the council's name and its definition of logistics, to indicate that logistics is a subset of supply chain management and that the two terms are not synonymous (*in* Ballou, 2007):

> Supply Chain Management encompasses the planning and management of all activities involved in sourcing

> and procurement, conversion, and all Logistics Management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, Supply Chain Management integrates supply and demand management within and across companies. Logistics management is that part of SCM that plans, implements, and controls the efficient, effective forward and reverse flows and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customer requirements.

Lambert et al. (1998) defined SCM as the integration of key business processes from end user through original suppliers that provide products, services, and information that add value for customers and other stakeholders.

Mentzer et al. (2001) define SCM as the "systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within a supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole." The same authors define supply chain as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer". According to Giunipero et al. (2008), the definition by Mentzer et al. (2001) is the most encompassing. Giunipero et al. (2008) explains that the definition suggests that SCM activities should include integration behaviour on the part of a firm, which would consist of a firm's customer and supplier base. Additionally, the firms involved in the supply chain should mutually share information, risks and rewards, as well as cooperate on activities performed within the chain.

Modern industrial enterprises typically involve multiproduct, multi-purpose, and multi-site facilities operating in different regions and countries and dealing with global customers. In a context of multi-enterprise networks, the issues of global enterprise planning, coordination, cooperation, and robust responsiveness to customer demands are critical for ensuring effectiveness, competitiveness, sustainability and growth along with investment and operating costs reduction (Papageorgiou, 2009). Supply chain analysis is a key to achieving enterprise efficiency as a system view is taken. Companies cannot be competitive without considering supply chain activities, because a single company can rarely control the production of a commodity together with sourcing, distribution, and retail (Papageorgiou, 2009). Furthermore, supply chains compete to increase their market shares and, even if they are not facing any competitor, they should be prepared for possible future competitive situations (Farahani et al., 2014).

2.2 Planning the supply chain network

Management of supply chains is a complex task mainly due to the large size of the physical supply network and its inherent uncertainties. As the physical structure of a supply chain influences its performance (Shen, 2007), determining such a structure is considered one of the most important stages as it affects future tactical and operational decisions of the chain (Farahani et al., 2014).

Competitiveness should also be considered in all stages of designing new supply chains (Farahani et al., 2014), since in a highly competitive environment improved decisions are required for efficient supply chain management at both strategic and operational levels (Papageorgiou, 2009).

Lambert et al. (1998) consider the structure of the supply chain, the network of members and the links between them, to be one of the three essential elements of the supply chain management. The other two elements being: the business processes (the activities that produce a specific output of value to the customer) and the business components (the managerial variables with which the business processes are integrated and managed). The design of the supply chain network (SCN) depends on the identification of the critical members of the supply chain and their tiers, and on the different types of process links across the SC (Lambert et al., 1998).

SCN design (or planning) involves several decisions, such as the number, location, and capacity of warehouses and manufacturing plants of a company or a set of collaborating companies (Meixell and Gargeya, 2005; Melo et al., 2009; Klibi et al., 2010); the flow of material through the logistics network (Melo et al., 2009); the assignment of each market to one or more locations (Meixell and Gargeya, 2005); the selection of suppliers for sub-assemblies, components, and materials; subcontractors; and 3PLs (third part logistics) (Meixell and Gargeya, 2005; Klibi et al., 2010), as illustrated in Figure 1.

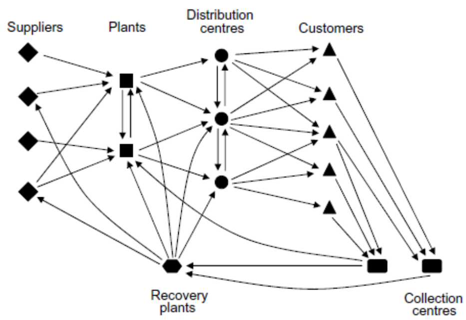

Figure 1 A generic supply chain network (Melo et al., 2009).

Global supply chain design extends this definition to include selection of facilities at international locations and the special globalization factors that this involves (Meixell and Gargeya, 2005). Figure 2 depicts a global supply chain network.

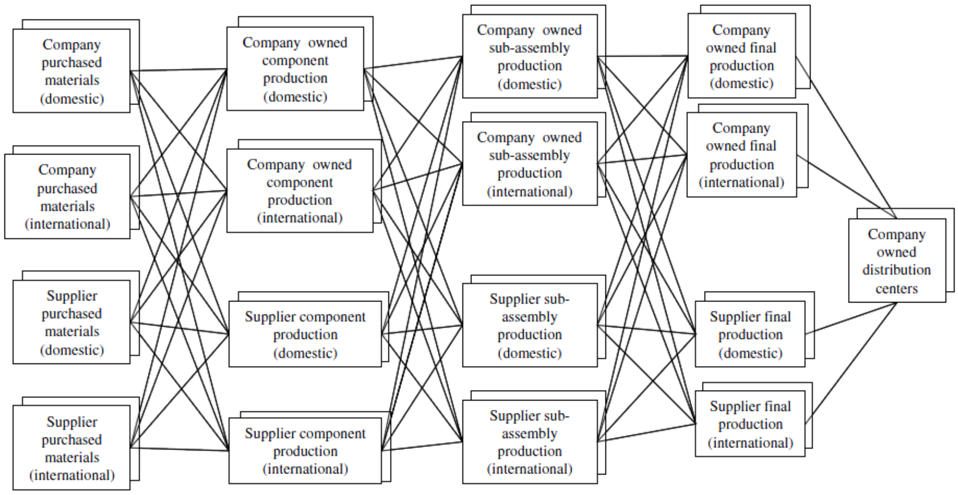

Figure 2 Alternative production locations in a global supply chain (Meixell and Gargeya, 2005).

The decisions of SCN design are at the strategic level, and have a long-lasting effect on the firm (Melo et al., 2009; Klibi et al., 2010). These strategic decisions must be made here-and-now but, after an implementation period, the SCN will be used on a daily basis for a long planning horizon (Klibi et al., 2010). In general, a network design project starts with the identification of potentially interesting sites for new facilities and the required capacities and, typically, large amounts of capital must be allocated to a new facility; thus, making this type of investment a long-term project (Melo et al., 2009). Although usually no design decisions are made on the tactical or even operational level, a number of issues are strongly related to them such as plant production planning and scheduling, inventory control policies, the choice of transportation modes and capacities, vehicle routing, and warehouse layout and management (Melo et al., 2009; Papageorgiou, 2009; Ramezani et al., 2014; Garcia and You, 2015). Thus, to achieve important cost savings, the supply chain should be optimized as a whole, that is, the major cost factors that can influence the performance of the supply chain should be considered simultaneously when making such decisions (Shen, 2007).

In addition to the great level of investments and the long-term impact of the decisions, there are other complexity factors in the design of the SCN. The first factor is industry structure and decoupling points, for example, problems involving complex manufacturing make-to-order processes (Klibi et al., 2010). Moreover, changes of multiple natures during a facility lifetime may turn a good location today into a bad one in the future (Melo et al., 2009). Furthermore, global supply chains design is even more difficult to manage namely because of increased transportation costs, inventory cost trade-offs due to increased lead-time in the supply chain, cultural differences that might diminish the effectiveness of business processes (Meixell and Gargeya, 2005), and other factors such as transfer prices, tariffs, tax regulations and trade barriers must also be accounted for (Klibi et al., 2010). Global supply chains also carry unique risks that influence performance, including variability and uncertainty in currency exchange rates, economic and political instability, and changes in the regulatory environment (Meixell and Gargeya, 2005). Day-to-day procurement, production, warehousing, storage, transportation, and demand management decisions generate product flows in the network, with associated costs, revenues, and service levels. The adequate design of a supply chain network requires the anticipation of these future activity levels (Klibi et al., 2010, Garcia and You, 2015). Henceforth, a rolling horizon decision-making method, which is a common business practice in this context (Sethi and Sorger, 1991), should be adopted in order to adjust to constant market changes.

Despite a rich literature on SCN design, most published works consider only a subset of these issues (Klibi et al., 2010). In short, the SCN design problem is the reengineering of such networks to enhance value creation in the companies involved. In general, SC networks are composed of five main entity types: i) external suppliers, ii) plants manufacturing intermediate and/or finished products, iii) distribution and/or sales centers, iv) demand zones, and v) transportation assets. In order to reengineer an existing SCN, an alternative potential network, including all possible options regarding supply, location, capacity, marketing, and transportation must be elaborated (Klibi et al., 2010). The main strategic questions addressed using this generic SCN design approach are the following: Which markets should we target? What delivery time should we provide in different product markets and at what price? How many production and distribution centers should be established? Where should they be located? Which activities should be externalized? Which partners should we select? What production, storage, and handling technologies should we adopt and what should their capacity be? Which products should be produced / stored in each location? Which factory / distribution / demand zones should be supplied by each supplier / factory / distribution center? What means of transportation should be used? Recovery and revalorization activities can also be considered. These strategic questions are not usually examined all together, but rather in isolation or at most few at a time (Klibi et al., 2010).

The choice of performance metrics to assess the quality of network designs is another important challenge. Such measures can be used to either design a system with appropriate level of performance or compare alternative systems (Papageorgiou, 2009). Quantitative performance measures can include: i) measures based on customer responsiveness (fill rate maximization, product lateness minimization, and customer response time or lead-time minimization) and ii) measures based on financial flow (cost minimization, sales and profit maximization, inventory investment minimization, and return on investment maximization) (Papageorgiou, 2009). As large investments are often required to implement strategic SCN decisions, managers require an assessment of return on investments before making such decisions (Klibi et al., 2010).

2.3 Modeling the supply chain network

Supply chain design and planning determines the optimal infrastructure (assets and network) and seeks to identify how best to use the production, distribution, and storage resources in the chain to respond to orders and demand forecasts in an economically efficient manner (Papageorgiou, 2009). According to Melo et al. (2009), the supply chain configuration problem involves generic facility location setup, but also other areas such as procurement, production, inventory, distribution, and routing. The need for coordinated planning of these areas was early recognized by the management science community and led to the development of mathematical models (Papageorgiou, 2009). The first facility location models have gradually evolved to design distribution networks (Sadjady and Davoudpour, 2012) considering the supply chain as a whole (Melo et al., 2009).

According to Papageorgiou (2009), supply chain models can be either mathematical or simulation-based. Mathematical programming models are developed to optimize high-level decisions involving unknown configurations, taking an aggregate view of the dynamics and detail of operation, while simulation models can study the detailed dynamic operation of a fixed configuration under operational uncertainty and evaluate the expected performance measures for the fixed configuration.

In fact, location models have been studied in various forms for hundreds of years (ReVelle et al., 2008). The contexts in which these models have been proposed may differ; however, their main features are similar: the known location of customers and facilities whose location is to be determined in a given space, while optimizing an objective function (ReVelle et al., 2008). Latter, within the context of supply chain management, location models were expanded.

Early research was mainly focused on static and discrete facility location problems (Melo et al., 2009; Papageorgiou, 2009; Klibi et al., 2010). In a discrete facility location problem (FLP), the selection of the sites where new facilities are to be established is restricted to a finite set of available candidate locations and the set of demand zones that need to be satisfied are at known and given locations. On the other hand, continuous models typically assume that facilities can be located anywhere, while demand points are often taken as being at discrete and known locations. (ReVelle et al., 2008; Melo et al., 2009; Ulukan and Demircioğlu, 2015).

Sadjady and Davoudpour (2012) argue that Weber's studies in 1909, which led to his industrial location theory, should be considered the first studies in FLP. The Weber problem consists of locating a single facility to serve *m* demand points with coordinates (x_i, y_i) with *i*=1,…, *m* and weights (w_i) with *i*=1,…,*m*. Distances in the Weber problem are often taken to be straight-line or Euclidean distances. The problem is to find a location for a single facility, with coordinates (x_0, y_0), that minimize the demand-weighted total distance (ReVelle et al., 2008).

Discrete facility location problems (FLP) are concerned with choosing the best location for facilities from a given set of potential sites such that the total cost is minimized while satisfying customers' demand. The uncapacitated facility location problem (UFLP) assumes that each facility has no limit on its capacity and that each customer is supplied by exactly one facility. The simplest forms of a UFLP are the Simple Plant Location Problem (SPLP) and the p-median problem (Ulukan and Demircioğlu, 2015). Given a set of possible locations for establishing new facilities (e.g., plants or warehouses), in the SPLP one wishes to determine the location of the supplier of a single product to a set of known customers, such that the total cost incurred is minimized (Krarub and Pruzan, 1983). Although with an uncertain origin, Krarub and Pruzan (1983) refer the works of Kuehn and Hamburger, in 1963, Manne, in 1964, and Balinski, in 1963 as the first explicit formulations of SLPL. The p-median problem is a translation of the Weber problem into a graph version by Hakimi, in 1964, that showed that an optimal solution for each problem is provided by facilities located just in the nodes of the graph (Bruno et al., 2014). In the p-median problem, p facilities are to be selected from a given set of $n \geq p$ facilities, in order to minimize the total weighted distances or costs for supplying customer demands, assuming that all candidate sites involve the same setup cost to establish a new facility (Melo et al., 2009).

In ReVelle et al. (2008) categorization, analytical models are based on a large number of simplifying assumptions. For example, a typical analytic model assumes that demands are uniformly distributed across a service region and admit closed-form expressions for the total cost, typically as a function of the total number of facilities being located. However, the stringent assumptions made by this class of models make them of limited value for decision-making for practical location problems ReVelle et al. (2008).

One of the most important extensions of the UFLP is the Capacitated Facility Location Problem (CFLP), in which exogenous values are considered for the maximum demand that can be supplied from each potential site (Melo et al., 2009). In the Single Source Capacitated Facility Location Problem (SSCFLP) each customer is assigned to one facility that must supply its entire demand. The total demand of the customers assigned to each facility cannot exceed the capacity of the aforementioned facility. Each used facility implies an opening cost; thus, the objective is the minimization of the total cost, which includes the cost of opening the facilities and the cost of suppling the customers (Ulukan and Demircioğlu, 2015). This problem is, computationally, a harder problem and is usually referred to as the set partitioning problem (Klibi et al., 2010).

All of the above mentioned models have several common characteristics namely, a single-period planning horizon, deterministic demand and costs, a single product, and one type of facility and involve location–allocation decisions (Melo et al., 2009; Klibi et al., 2010). However, these models are clearly insufficient to cope with many realistic facility location settings. Therefore, several extensions to the basic problems have been considered and studied (Melo et al., 2009; Klibi et al., 2010).

An important development was the consideration of a longer planning horizon, that is usually divided into several time periods, which lead to the multi-period location problem. In this problem, parameters change over time, although in a predictable way, and the goal is to adapt the configuration of the facilities to these changes (Melo et al., 2009). Some of the proposed models are static, that is, they involve design decisions only at the beginning of the planning horizon, but they use several planning periods to anticipate more closely operational decisions. Dynamic models have also been proposed, in this case, it is possible to revise design decisions (number, location, technology, and capacity of facilities; sourcing and marketing policies) at the beginning of each planning period (Klibi et al. 2010). The recognition of uncertainty, usually associated with demand or costs, led to the introduction of stochastic components (Melo et al. 2009).

Another aspect to drive location problems to be more realistic is the consideration of different types of facilities (multiple echelon), each of which with a specific role, such as production, warehousing, etc. and with a flow between them (Melo et al., 2009). Models have also been developed to cope with multi-commodity problems (Melo et al., 2009). In the last few years, major efforts have been devoted to the development of location models with a much more detailed anticipation of transportation (routing and mode) and inventory management decisions (Klibi et al., 2010).

More recently, models have been proposed to address the reverse logistics flows, which refers to the activities dedicated to the collection and/or recovery of product returns or packages, and also integrated logistics (forward and reverse logistics) (Melo et al., 2009; Pishvaee et al. 2010).

Melo et al. (2009) provide a comprehensive literature review on discrete facility location problems in the context of supply chain management, identifying 120 articles published between 1998 and 2008. In their first analysis, four basic features are taken into account, namely: multi-echelon facilities, multiple commodities, single or multi period and deterministic or stochastic parameters. The results of the analysis show that most of the literature deals with single-period (approximately 82% of the surveyed papers) and deterministic (approximately 80% against 20% of stochastic models) problems. Different sources of uncertainty can be found in the literature, namely: customer demands, exchange rates, travel times, amount of returns in reverse, supply lead times, transportation costs, and holding costs. Almost 80% of the surveyed papers refer to one or two echelons and among these, around two-thirds model location decisions in a single echelon. Moreover, as previously mentioned, it is generally assumed that customers can only be supplied from the closest echelon. The authors consider, however, that this assumption is not valid in many SCND design problems, where it may be possible to have direct shipments from upper echelon facilities to customers or to facilities not in the echelon immediately below. Another important characteristic of many supply chain networks regards flows in the same echelon. Around 59% of the papers consider a single product.

In a second analysis, the authors identify other decision, besides the classical location-allocation decisions. About 60% of the articles feature additional decisions, and facility location decisions are frequently combined with inventory and production decisions. In contrast, procurement, routing, and the choice of transportation modes (alone or integrated with other types of decisions) have not received much attention. Capacity expansion decisions were found just in eight articles, most of them combined with multi-period location decisions. Some authors confine capacity decisions to one specific echelon only. Inventory planning decisions are mostly focused on one echelon, namely the one involving storage. Nevertheless, five articles propose inventory decisions in several layers. The small number of papers integrating decisions regarding procurement, routing, and the choice of transportation modes with other decisions, in particular those focusing on the strategic planning level, show that existing literature is still far from combining many aspects relevant to SCM.

A final analysis was made on the type of supply chain performance measures used, the methodology followed to solve the problems, and applications of facility location models to strategic supply chain planning. The majority of the papers (75%) feature a cost minimization objective. Moreover, this objective is typically expressed as a single objective through the sum of various cost components that depend on the set of decisions modelled. In contrast, profit maximization has received much less attention (16%). Two different categories of profit maximization can be found in the literature: i) maximization of revenues net of operational costs (operational income), and ii) after-tax profit maximization (net income). The last and smallest group of articles (9%) refers to models with multiple and conflicting objectives. In this case, in addition to economic factors, measures based on resource utilization and customer responsiveness are also considered. The latter include fill rate maximization, i.e., the maximization of the fraction or amount of customer demand satisfied within the promised delivery time, and product lateness minimization, i.e., the minimization of the time elapsed between the promised date and the actual product delivery date.

Regarding solution methodologies, about 75% of the reviewed papers solve the problems through a specific purpose method developed for the problem in hands. An exact method is used in 30% of the cases and they include branch-and-bound, branch-and-cut, column generation, and decomposition methods. Among the exact approaches, branch-and-bound algorithms have been a popular solution scheme, sometimes also combined with Lagrangean relaxation or heuristic procedures to obtain bounds. When the number of discrete variables is large, and this often occurs when the strategic location decisions refer to more than one facility echelon in the supply chain network, then the resulting models are comparatively more complex and realistically sized problems can only be solved by a heuristic method (45% of the problem approaches use such a method). The remaining papers (25% of the reviewed ones) use a general purpose solver software. Finally, 68% of the articles report on case studies, while the remaining 32% use randomly generated data in an industrial context.

Meixell and Gargeya (2005) reviewed model-based literature from 1982 to 2005, specifically addressing the global supply chain design problem and selected eighteen articles based on their relevance. Global supply chain design models are a special class of supply chain design models, due to the differences in the cost structure and additional complexity of international logistics. Most of the models proposed select locations for production and/or distribution facilities in global supply chains. Twelve of the proposed models consider decisions on material flows in the form of shipment quantities between production, distribution, and market locations; however, only five of them consider the supplier selection problem; a shortcoming in the author's opinion considering the extent of outsourcing in practice today. Two of the models proposed also address capacity decisions, both how much and when. Regarding application areas, one of the proposed models address problems in the following fields: financing arrangements, product allocation, production shifting, and transportation mode selection.

Regarding performance measures, half of the articles analysed by Meixell and Gargeya (2005) consider profit, operating profits, or after-tax profits. From the remaining ones, eight minimize cost, one minimizes production and distribution times (instead of cost or profit), two consider flexibility in global supply chains by proposing a cost-based model and then investigating the value of having options to assign production to facilities after observing actual currency exchange rates, and another maximizes robustness of the cost-based solution, also under conditions of uncertain currency exchange rates.

Concerning integrating decisions, Meixell and Gargeya (2005) identified seven articles that co-ordinate multiple production sites and multiple markets, two that consider multiple supplier sites for multiple production sites and six that coordinate multiple production–distribution tiers for multiple markets. All eighteen articles provide an exchange rate parameter to convert local currencies to a common currency; six account for variability in the exchange rate by using a time index and seven use a random variable to introduce uncertainty on the global supply chain design problem. Eleven of the models incorporate tariffs or duties, and eight consider non-tariff barriers. Corporate income taxes are considered in eight articles. Most of the articles provide the structure to explicitly evaluate the impact of extraordinary transportation costs in global supply chains, but only two incorporate the impact of long transit times in cost terms. The authors conclude that despite some advances, few models comprehensively address outsourcing, integration, and strategic alignment in global supply chain design.

In order to update the literature review, we searched at b-on (Online Knowledge Library) for articles published between 2008 and 2019 in academic journals with peer review using "supply chain network design model" and "supply chain network design + finance" in the title. We found 83 articles (see Table 4), after excluding surveys, non-printed articles, articles of a qualitative nature, and articles with models covering only tactical and operational issues. We have followed a structure of analysis similar to that of Melo et al. (2009).

We began by analysing problem description characteristics, where we have included four basic features: number of echelons, number of locations, number of products, and planning horizon. We found that the great majority of the articles address multi-echelon and multi-location, representing, respectively, 99% and 98%, respectively, of the total articles. Only 61% of the articles deal with multi-product and even a lesser number deals with a multi-period planning horizon (49%). Regarding stochastic elements, we found that 58% consider some sort of uncertainty. Among those, demand is the most common source of uncertainty, which has been considered in 74% of the works, followed by costs (28%). Other sources of uncertainty are also considered, namely:

capacities, amount of products returned, uncertainty in life cycle, and disaster/risk scenarios. Recall that in the review of Melo et al. (2009) only 20% of the models included stochastic elements, which means that researchers are turning their attention to one of the challenging problems in SCM.

Our analysis follows with the decision types considered. Besides the usual decisions on location and flows, about 79% of the articles feature decisions on quantities produced/transported. In contrast, only 25% feature decisions on facilities capacity. Inventory decisions and the choice of routes and transportation modes integrated in strategic models have not received much attention. However, new types of decisions are being addressed, namely seven articles decide on the type of technologies to use, seven include some sort of financial decisions, and four decide on supplier selection.

The majority of the papers (73%) features a cost minimization objective, while profit maximization has received much less attention (18%). A very considerable group of articles (28%) refers to models with multiple objectives and, among these, 83% combine cost minimization or profit maximization with a second objective function. From the articles considering multiple objective function, we highlight the high number of articles that aim to minimize environmental impact (57%). Other measures based on customer satisfaction, delivery lead times, and finance have also been considered.

Regarding solution methodology, about 53% of the articles use an exact method and 47% use a heuristic one.

We can conclude that the problems addressed are becoming more complex – most of the models proposed are multi-echelon, multiple location, and multiple product (59%) and a big part (47%) is also multi-period; most of them incorporate uncertainty mainly to represent reality with more accuracy, not only in demand, but also in costs and other elements. In addition, the objective function is moving from the traditional cost minimization to a bi-objective (sometimes multi-objective) function, where environmental concerns are evident.

In the same line of thought, we address a deterministic multiple-period, multi-echelon, and multi-product SCND problem that considers simultaneously operations and financial decisions, in order to maximize the company value (measured through shareholder value analysis (SVA) method). Note that, only 47% of the articles we have reviewed address such a problem. Moreover, from the articles reviewed by Melo et al. (2009) only 18%, 20% and 41% are, respectively multi-period, multi-echelon (more than two-echelons), and multi-product. At the strategic level we make decisions on the number and location of facilities (plants, warehouses, and distribution centers), and also on the links among them. At the tactical level, we decide on the quantities to produce at each plant and for each facility, we decide on the quantities to transport and to store, ensuring satisfaction of demand at each customer zone. As financial decisions, we consider the amount to invest, the source of the money needed to make the investments (cash, bank debt, or capital entries from shareholders) and the repayments policy to the bank. Although we do not consider uncertainty, we consider a dynamic environment and thus, all decisions are at each time period; this way the company is able to adjust to changes in market conditions. Our problem is formulated as a MILP, which we then solve exactly by resorting to Gurobi.

Article	Solution method		Problem description								Data Type		Objective function			Decisions						
			Echelons		Locations		Products		Planning horizon													
	Exact solution	Heuristic	Single	Multi	Single	Multi	Single	Multi	Single-period	Multi-period	Deterministic	Stochastic	Cost min	Profit max	Other	Location	Flows	Quantities	Capacity	Inventory	Transportation	Others
Ahn et al. (2015)	v			v		v		v		v	v		v			v	v	v				
Akgul et al. (2012)	v			v		v		v	v			v	v			v	v	v			v	
Alavi and Jabbarzadeh (2018)		v			v	v		v		v		v		v		v						v
Altiparmark et al. (2009)		v		v		v		v	v		v		v			v	v					
Amalnick and Saffar (2017)	v			v		v		v		v		v	v		v	v	v	v			v	v
Amin and Baki (2017)	v			v		v		v		v		v		v	v	v	v	v				
Arabi et al. (2019)	v			v		v	v			v		v	v			v	v	v		v		
Arampantzi et. al (2019)	v			v		v		v		v	v		v			v	v	v	v		v	v
Azad et al. (2014)		v		v		v	v		v			v	v			v	v	v				
Balaman and Selim (2014)	v			v		v	v		v		v			v		v	v	v				
Barzinpour, F. and Taki, P. (2018)		v		v		v	v		v		v			v		v	v	v				
Bidhandi et al. (2009)		v		v		v		v	v		v		v			v	v		v			
Bouzembrak et al. (2013)	v			v		v	v		v			v	v			v	v	v				
Bowling et al. (2011)	v			v		v		v	v		v		v			v	v	v				
Cafaro and Grossmann (2014)		v		v		v	v			v	v				v	v	v	v	v			
Cardoso and Barbosa-Póvoa (2013)	v			v		v		v		v		v			v	v	v	v	v	v		v
Chaabane et al. (2012)	v			v		v		v		v	v		v		v	v	v	v				
Chalmardi and Camacho-Vallejo (2019)		v		v		v	v		v		v		v			v	v	v				v
Coskun et al. (2016)	v			v		v		v	v		v				v	v	v	v				
Dai and Zheng (2015)		v		v		v		v		v		v		v		v	v	v	v			

Table 1 Summary of the literature review on supply chain network design (2008-2019) (i).

Article	Solution method		Problem description: Echelons		Problem description: Locations		Problem description: Products		Problem description: Planning horizon		Data Type		Objective function			Decisions						
	Exact solution	Heuristic	Single	Multi	Single	Multi	Single	Multi	Single-period	Multi-period	Deterministic	Stochastic	Cost min	Profit max	Other	Location	Flows	Quantities	Capacity	Inventory	Transportation	Others
Fathollahi-Fard et al. (2018)		√		√		√		√	√			√	√			√	√	√				
Fazli-Khalaf et al. (2017)	√			√		√	√		√			√	√		√	√	√	√	√			
Fernandes et al. (2013)	√			√		√		√		√	√			√		√	√		√		√	√
Firoozi et al. (2013)		√		√		√	√		√			√	√			√	√	√				
Firoozi and Ariafar (2016)		√		√		√	√		√			√	√			√	√	√		√		
Gan et al. (2014)		√		√		√		√	√		√		√			√	√	√				
Gao and You (2015)		√		√		√	√			√	√			√		√	√	√	√		√	
Garcia and You (2015)		√		√	√			√	√		√			√			√	√	√			√
Garcia-Herreros et al. (2014)	√		√			√		√		√		√	√			√	√		√			
Gebreslassie et al. (2012)	√			√		√		√		√		√	√		√	√	√	√		√	√	√
Georgiadis et al. (2011)	√			√		√		√		√		√	√			√	√	√		√		
Ghahremani-Nahr, et al. (2019)		√		√		√		√		√		√	√			√	√	√				√
Guillén and Grossmann (2009)	√			√		√		√		√		√			√	√	√		√			√
Guillén and Grossmann (2010)	√			√		√		√		√		√			√		√					√
Guillén et al. (2010)		√		√		√		√		√	√		√		√	√	√		√	√	√	√
Hamidieh. et al. (2017)	√			√		√		√	√			√	√		√	√	√	√				
Hassan and Mahdis Haghighi (2011)		√		√		√	√		√		√		√			√	√	√				
Jabbarzadeh et al. (2014)	√			√		√	√			√		√	√			√	√	√		√		
Jindal and Sangwan (2014)	√			√		√		√	√			√		√		√	√	√		√		
Kaboli and Camacho-Vallejo (2019)		√		√		√	√		√		√		√		√	√	√	√				
Kadambala et al. (2017)		√		√		√	√		√		√			√	√		√					
Kannan et al. (2009)	√		√		√	√			√	√		√			√		√					√

Table 2 Summary of the literature review on supply chain network design (2008-2019) (ii).

Article	Solution method		Problem description: Echelons		Problem description: Locations		Problem description: Products		Problem description: Planning horizon		Data Type		Objective function			Decisions						
	Exact solution	Heuristic	Single	Multi	Single	Multi	Single	Multi	Single-period	Multi-period	Deterministic	Stochastic	Cost min	Profit max	Other	Location	Flows	Quantities	Capacity	Inventory	Transportation	Others
Kazemzadeh and Hu (2013)	v			v		v	v		v			v		v	v	v	v	v				
Kilic and Tuzkaya (2015)	v			v		v		v		v		v		v		v	v	v		v		v
Lee and Dong (2009)		v		v		v	v			v		v	v			v	v	v				
Longinidis and Georgiadis (2011)	v			v		v		v		v		v			v	v	v	v		v		
Longinidis and Georgiadis (2014)	v			v		v		v		v		v			v	v	v	v	v	v		
Mahamoodi (2019)		v		v	v			v	v			v	v		v		v	v		v		v
Min and Ko (2008)		v		v		v		v		v	v		v			v	v		v			
Mohammadi et al. (2017)	v			v		v		v		v	v				v	v	v	v	v	v		
Monteiro et al. (2010)		v		v		v		v	v			v	v			v	v	v		v		
Nagurney and Nagurney (2012)		v		v		v	v		v		v		v			v	v	v				
Osman and Demirli (2010)	v			v		v		v		v	v		v		v		v					v
Paksoy et al. (2013)	v			v		v	v		v			v		v		v	v	v				
Pant et al. (2018)		v		v		v		v	v		v		v			v	v	v				
Park et al. (2010)		v		v		v	v		v		v		v			v	v	v				
Patil et al. (2018)	v				v	v	v		v		v		v									v
Pazhani et al. (2013)	v			v		v		v		v	v		v			v	v	v				
Pimentel et al. (2013)		v		v		v		v		v		v	v			v			v			v
Pishvaee et al. (2010)		v		v		v	v		v		v		v		v	v	v	v	v			
Pishvaee et al. (2011)	v			v		v	v		v			v	v			v	v					
Puigjaner and Laínez (2008)	v			v		v		v		v		v			v	v	v	v				
Qiang (2015)		v		v	v		v			v	v			v				v	v			

Table 3 Summary of the literature review on supply chain network design (2008-2019) (iii).

Article	Solution method		Problem description								Data Type		Objective function			Decisions						
			Echelons		Locations		Products		Planning horizon													
	Exact solution	Heuristic	Single	Multi	Single	Multi	Single	Multi	Single-period	Multi-period	Deterministic	Stochastic	Cost min	Profit max	Other	Location	Flows	Quantities	Capacity	Inventory	Transportation	Others
Ramezani et al. (2014)	√			√		√	√			√	√				√	√	√					√
Roni et al. (2014)		√		√		√	√		√		√		√			√	√	√				
Sadeghi and Nahavandi (2018)	√			√		√		√		√	√		√		√	√	√	√			√	
Sadjady and Davoudpour (2012)		√	√			√		√	√		√		√			√	√		√		√	
Savadkoohi et al. (2018)	√			√		√		√		√		√	√			√	√	√		√		
Selim and Ozkarahan (2008)	√			√		√		√	√			√	√		√	√	√	√				
Hosseini-Motlagh et. al (2016)	√			√		√	√			√		√	√			√	√	√				
Talaei et al. (2016)	√			√		√		√	√			√	√		√	√	√	√				
Tan et al. (2019)		√		√		√		√	√			√	√			√	√	√				
Taxakis, K. and Papadopoulos, C. (2016)		√		√		√		√	√	√	√		√			√	√	√		√		
Vahdani et al. (2013)	√			√		√		√	√			√	√		√	√	√	√				
Wang (2009)		√		√		√	√		√			√			√	√	√	√				
Wang et al. (2011)		√		√		√	√		√			√	√		√	√	√					
Yao et al. (2010)		√		√		√		√	√			√	√			√	√			√		
Yavari and Geraeli (2019)		√		√		√		√		√		√	√		√	√	√	√	√	√		√
You and Grossmann (2008)		√		√		√	√		√			√	√			√	√					
Yu et al. (2014)	√			√		√	√		√		√		√		√	√	√	√				√
Yu et al. (2015)	√			√		√		√		√	√		√			√	√	√				
Yu et al. (2018)	√			√		√	√		√			√	√		√	√	√	√				
Zokaee et al. (2017)	√			√		√	√		√			√	√			√	√	√				√

Table 4 Summary of the literature review on supply chain network design (2008-2019) (iv).

2.4 Supply chain models with financial issues

As described in the previous section, we propose a MILP model that considers simultaneously operations and financial decisions. In order to understand the state of the art, this section reviews works that incorporate financial aspects. Although many researchers have mentioned the importance of financial considerations in the SCM context (Applequist et al., 2000; Shapiro, 2004; Meixell and Gargeya, 2005; Shah, 2005; Hammami et al., 2008; Puigjaner and Guillén, 2008; Melo et al., 2009; Papageorgiou, 2009; Longinidis and Georgiadis, 2011), not much research can be found considering them. Applequist et al. (2000) highlight the importance of the coordination of the activities of the different SC entities and specifically at the enterprise level, which requires integration of the logistics and manufacturing aspects with strategic business and financial decisions. Shapiro (2004) suggests that strategic decisions of the SCN design are critical inputs to financial planning exercises. Therefore, the link diferent SC entities and corporate finances should be evaluated when modelling a SC. Shah (2005) argues that combined financial and production-distribution models should be considered in the area of SCM. Melo et al. (2009) consider that financial factors are among the issues that have a strong impact on the configuration of global supply chains. Other authors (Meixell and Gargeya, 2005; Hammami et al., 2008; Papageorgiou, 2009; Klibi et al., 2010) refer the importance of financial factors such as transfer pricing, corporate income taxes, currency exchange rate, tariffs, duties, transportation issues, and constraints of local content rules and offset requirements, in a global network design context.

According to Elgazzar et al. (2012), managers should be aware of the connection between supply chain performance and the financial strategy of the company and how their operational actions can impact the overall financial performance. Presutti and Mawhinney (2007, *in* Elgazzar et. al., 2012) stated that 70% or more of manufacturing companies' expenditures are due to supply chain activities, which highlights the potential impact of an effectively managed supply chain in contributing to the overall improvement of financial performance.

Several authors (e.g., Puigjaner and Guillén, 2008; Longinidis and Georgiadis, 2011, 2014; Ramezani et al., 2014; Mohammadi et al., 2017) argue that financial operations are supplementary to production and distribution operations, because they ensure their financing. Moreover, sustainability and growth of the SCN rely heavily on financing. Expansion in new emerging markets, investment in new production processes, equipment, and innovative products need new funds (Longinidis and Georgiadis, 2014). These authors go further and propose an integrated analysis (with simultaneous operations and financial decisions), by including the more general objective of maximizing the shareholder value of the firm as opposed to the common optimization of traditional KPIs (key performance indicators), such as cost or profit.

The view that the supply chain strategy employed by the firm can have a significant effect upon shareholder value was already supported by Christopher and Ryals (1999), despite its relative inattention in the shareholder value literature. According to the authors' framework, the four drivers of shareholder value are revenue growth, operating cost reduction, fixed capital efficiency, and working capital efficiency; all being directly and indirectly affected by logistics management and SC strategy. Regarding revenue growth, studies suggest a positive causality between logistics service and sales volume and customer loyalty. The potential for reducing operating costs through logistics and SCM is considerable, since a large proportion of such costs, in a typical business, are driven by logistics practices and the quality of SC relationships. Additionally, logistics tend to be fixed asset intensive by its nature and the desire to reduce fixed asset investment, as a way to improve efficiency, leads to distribution networks rationalization, such as third-party logistics subcontracting, lease instead of buying, among others. Logistics and SC strategy are also linked to the working capital, namely long pipelines that generate more inventory, order fill and invoice accuracy that directly impact accounts receivables and procurement policies that affect cash flows. Working capital requirements can be reduced through time reduction in the pipeline, eliminating non-value adding time in the SC, and subsequent order-to-cash cycle times (from materials procurement through the sale of finished products).

In matters of financial issues integration with SC decisions, Badell et al. (1998) presented an original research, though at the plant level only. The authors introduced a hybrid strategy for incorporating financial considerations into an advanced planning and scheduling application that implemented metaheuristic optimization algorithms. The final purpose was to guarantee the liquidity of the schedule that satisfied a set of due-dates previously negotiated with the customers. The initial goal of checking the feasibility of the planning decisions from a financial point of view was later extended by Romero et al. (2003) to include the more ambitious objective of optimizing operations and finances in unison. To achieve this integration, the authors built a deterministic multi-period mathematical model for the batch chemical process industry based on the short-term cash management model proposed by Orgler (1969, *in* Romero et al., 2003). Orgler's model maximizes the sum of payments, whether or not prompt payment discounts were taken into account, plus the marketable security revenues minus the costs of the short-term credit line. In Romero et al. (2003), the cash management formulation was widened to include further financial variables and constraints. In particular, the possibility of pledging receivables, as a way of obtaining further funding, was introduced into the model. Moreover, the objective function maximizes the cash flow of dividends, that is, the amount of cash that can be withdrawn from the company at a given instant of time, as a measure of shareholder value. This line of research was pursued by Badell et al. (2004; 2005) that introduced a mixed-integer linear programming model (MILP) formulation to address the integration of financial aspects with short-term planning in the batch process industry, including retrofitting activities at the plant level. These models demonstrate how to integrate cash flow and budgeting models with planning and scheduling models.

Financial considerations have also been introduced at plant level by Yi and Reklaitis (2004) that proposed two level parametric optimization model for the optimal design of batch storage networks integrating production decisions with financial transactions through cash flow assignment in each production activity. A cash storage unit is installed to manage the cash flows associated with production activities, such as raw material procurement, process operating setup, inventory holding costs, and finished product sales. Temporary financial investments as a mean to increase profit, are also considered. The objective function proposed minimizes the opportunity costs of annualized capital investment and cash/material inventory minus the benefit to stockholders. In a more recent work, Yi and Reklaitis (2007) developed a model in which multiple currency storage units are considered to manage the currency flows associated with multinational supply chain activities, investigating the influence of exchange rates and taxes on operational decisions (including raw material procurement, processing, inventory control, transportation, and finished product sales). The supply chain is modelled as a batch-storage network with recycling streams, for the chemical industry. Temporary financial investments, bank loans, and currency transfer between multiple nations are allowed, aiming at increasing the marginal profit.

Extensions to the methods presented in these works, from the plant level to the whole SC, are studied by Guillén et al. (2006; 2007). To addressed the importance of integrating planning and budgeting models in SCM, the authors introduce a deterministic MILP model, for a multiproduct, multi-echelon chemical supply chain, which optimizes planning/scheduling and cash flow/budgeting decisions simultaneously, in order to maximize the corporate value of the firm. Guillén at al. (2006; 2007) propose financials model based on that of Romero et al. (2003); however, they maximize the increment of shareholders' equity, rather than the cash flow of dividends. The main purpose of including this performance index is to improve the shareholders' value of the firm.

A general framework for the design of supply chains based on the development of holistic models that cover both operations and financial processes is discussed in Laínez et al. (2007). The authors apply mixed-integer modelling techniques and use variables and constraints related to both operations and finances. The corporate value of the firm is adopted as the objective to be maximized. Puigjaner and Guillén (2008) address the same problem, using a different method. They developed a multi agent system for SCM that integrates operational and financial decisions on a single platform. A financial module was constructed to optimize the financial variables associated with the SC operation and to ensure the firm's liquidity. It includes a linear programming model to determine short-term cash decisions, while maximizing the change in the equity of the company. The operations module incorporates a multi-agent simulator that addresses payments of raw materials, production, and transport utilities, as well as revenues from the sales. The financial part uses the mathematical formulation of Guillén et al. (2006) and optimizes the cash flows associated with SC operation, in order to increase the shareholder value of the firm. This cash management formulation allows payments to providers, short-term borrowing, pledging decisions, and buying/selling of securities devising.

Recognizing the importance of more realistic models, Puigjaner and Laínez (2008) developed a supply chain integrated solution with design-planning and financial formulation that incorporates uncertainty. The work starting point is the general framework for the SC design and planning presented by Laínez et al. (2007), which is then extended it in order to cope with demand, price, and interest rates uncertainties. A scenario based multi-stage stochastic mixed integer linear programming model is employed to address the problem and a model predictive control (MPC) methodology that comprises a stochastic optimization approach is proposed. MPC has the ability to anticipate future events and can take control actions accordingly. Although innovative, due to the consideration of financial aspects as endogenous variables, which model the financial operation and are optimized along with the other SCN design variables, this line of research, developed by Puigjaner and colleagues and Yi and Reklaitis (2004; 2007) lacks generality, as it is too focused on scheduling and planning problems for batch process industries.

In another line of research, financial aspects are considered as known parameters used in constraints and in the objective function. In a literature review from 1998 to 2008, Melo et al. (2009) identified articles contemplating financial factors in supply chains and grouped them into three categories. The first category, international factors, includes taxes, duties, tariffs, exchange rates, transfer prices, and local content rules. The second category comprises financing and taxation incentives offered by governments to attract facility investments in certain countries or regions. The last category refers to investment expenditures, which are usually limited by the total available budget and are modelled by budget constraints for opening and closing facilities. When the planning horizon includes multiple periods, budget limitations vary from period to period, thus constraining not only the location of facilities but also other strategic supply chain decisions. In a total of one hundred and twenty articles, only twenty-two include financial factors; from these ten belong to first category, five to the second, and seven to the third.

In our recent review we found eleven other articles (Tsiakis and Papageorgiou, 2008; Hammami et al., 2008 and 2009; Laínez et al., 2009; Sodhi and Tang, 2009; Protopappa-Sieke and Seifert, 2010; Longinidis and Georgiadis, 2011 and 2014; Moussawi-Haidar and Jaber, 2013; Ramezani et al., 2014; Mohammadi, 2017) that include financial factors. Tsiakis and Papageorgiou (2008) introduced a model for the design of a production and distribution network, through a MILP formulation, incorporating exchange rate and duties as constraints. The objective was to minimize total cost. Hammami et al. (2008; 2009) developed a multi-product and multi-echelon model, formulated as a MILP, which incorporates the factors considered relevant for the delocalization context. As financial factors, they considered transfer pricing, suppliers, and transportation costs allocation. Sodhi and Tang (2009) developed a linear programming model for supply chain planning similar to the asset-liability management model. The authors argue that a supply chain planning model with demand uncertainty is akin to an asset-liability management model with uncertain interest rate. They extend a general deterministic supply chain planning model using stochastic programming by incorporating demand uncertainty to consider unmet demand and excess inventory, and by incorporating cash flows to consider liquidity risk. The financial factors considered were cash flow management and borrowing constraints and maximization of the expected present value of the net cash in a given planning horizon.

Laínez et al. (2009) follow the work of Laínez et al. (2007) and present a model with a focus on the process operations and the product development pipeline management (PDPM) problem in which financial aspects, i.e. tax rate, debts, working capital, accounts payable, and accounts receivable are also considered. The corporate value (CV) of the firm is adopted as the objective to be maximized.

Protopappa-Sieke and Seifert (2010) presented a model that involves decisions on optimal purchasing order quantities with respect to capital constraints and payment delays. The results show the importance of payment delays and demonstrate the impact of capital on the total operational cost, the return on capital investment, and the total financial cost. They elaborate on the benefits of considering both operational and financial aspects in decision-making for the physical and financial supply chain.

Longinidis and Georgeadis (2011) proposed a model that integrates supply chain design decisions with financial considerations, based on the idea that all the establishment and operating costs have a direct effect on the company's financial statements. The objective is to maximize the company's shareholder value, measured by the Economic Value Added (EVA) through the operation of its supply chain network, taking into account several design, operating, and financial constraints.

Moussawi-Haidar and Jaber (2013) considered the problem of finding the optimal operational (how much to order and when to pay the supplier) and financial decisions (maximum cash level and loan amount) by integrating the cash management and inventory lot sizing problems. The results indicate that the optimal order quantity decreases as the retailer's return on cash increases.

Longinidis and Georgiadis (2014) introduce a model that incorporates sale and leaseback with supply chain network design decisions. By employing advance financial management methods, such as sale and leaseback (SLB), fixed assets could be the strategy to improve liquidity and strengthen credit solvency.

Ramezani et al. (2014) developed a closed-loop supply chain design model that incorporates the financial aspects (i.e., current and fixed assets and liabilities) and a set of budgetary constraints representing balances of cash, debt, securities, payment delays, and discounts in the supply chain planning. The objective function to be optimized is the change in equity.

Recently, Mohammadi et al. (2017) propose the design of a supply chain network in which operational and financial dimensions have been considered within strategic and tactical decision-making. A multi-echelon, multi-product, and multi-period problem is addressed, and three different objective functions, which are measures on value creation (corporate value, change in equity and EVA) were considered. From the experiments conducted, the authors were able to conclude that optimizing corporate value provides better results for the three measures considered.

Nevertheless, literature on supply chain models that incorporate financial aspects is still scarce. While some studies consider financial aspects as known parameters used in constraints and in the objective function, other studies consider financial aspects as endogenous variables. Nevertheless, the existing literature lacks generality as it is too focused on scheduling and planning problems within the batch process industry. Only three studies (Longinidis and Georgiadis, 2011; Ramezani et al., 2014; Mohammadi et al., 2017) address strategic decisions related with supply chain network in order to maximize companies shareholder value. Comparing our work with those, we will innovate in several ways, thus contributing to extend existing literature. We use shareholder value analysis to calculate shareholder value creation. Both the measure (SVA) and the method (discounted free cash flow) are considered by several authors (e.g., Mills and Print, 1995; Lambert and Burduroglu; 2000; Klibi et al., 2010) the best way to evaluate a company's value, since it considers the economic value rather than the accounting value of the company; Nevertheless, none of the studies uses it. Longinidis and Georgiadis (2011) work uses too many assumptions (e.g., cash flow calculations, the inexistence of an accounts payable policy, not making repayments to the bank) which are far from realistic, and only allows for decisions in the first year of the planning horizon. Ramezani et al. (2014) study is single product, while ours is multi-product. Mohammadi et al. (2017) work is focused on modelling the financial statement of a company disregarding operational decisions. Although being a four-echelon problem, location decisions are only made at the distribution center level. The only relevant conclusions are related with choosing the best objective function, and none of the operational decisions is reported. Furthermore, our work includes the possibility of closing facilities at any time period of the planning horizon, which is a novelty in literature.

After finding this gap in literature, our work develops a model to address the problem of a supply chain network design with financial considerations, in order to maximize shareholder value, calculated through the discounts free cash flow method. The chosen objective function is considered the best way to evaluate a company's value, as explained in next section.

2.5 Supply chain design and its relevance for shareholder value creation

Two SCND models, developed by Puigjaner and Guillén (2008) and Longinidis and Georgiadis (2011), include the more general objective of maximizing the shareholder value of the firm as opposed to the common optimization of traditional key performance indicators (KPIs)such as cost or profit. Shareholder value is the financial value created for shareholders by companies in which they invest (Christopher and Ryals, 1999) and was formally introduced by Alfred Rappaport in 1986 (*in* Blyth et al., 1986).

The supply chain strategy employed by the firm, including logistics decisions, can have a significant impact upon shareholder value creation (Walters, 1999). Walters (1999) reviewed the works that support this connection. One such work is that of Cooke (1995, *in* Walters, 1999), which evaluated the role of logistics in creating shareholder value based on the EVA concept and called the attention for the need of the logistics managers to look at the overall financial picture of their companies. Another such work by Coppacino (1997, *in* Walters, 1999), also supports this view and identifies the following three elements as the most important to shareholder value creation: i) cash, which is driven by revenues, costs and depreciation, and other non-cash expenses; ii) invested capital, which depends on current assets, current liabilities, net property/plant/equipment, and deferred charges; and iii) cost of capital. The author concludes that logistics decisions such as inventory management, customer service, facility utilization, among others, may affect the company overall value. In addition, effective logistics decision making requires familiarity with finance concepts and its implications. Having these ideas as a reference, Walters (1999) discusses the issues underlying shareholder value management and planning and proposes a model linking EVA, operating management, and logistics options, in order to enable managers to explore the impact of different logistics implementation options on shareholder value.

A similar view is put forward by Christopher and Ryals (1999) that argue that supply chain strategy has a central position in shareholder value creation, despite its relative inattention in the shareholder value literature, and explore the corresponding connections. The authors identify revenue growth, operating cost reduction, fixed capital efficiency, and working capital efficiency as the drivers of shareholder value creation, arguing that all of them are directly and indirectly affected by logistics management and SC strategy. Regarding revenue growth, studies suggest a positive causality between logistics service and sales volume, and customer loyalty. The potential for operating cost reduction through logistics and SCM is considerable, since a large proportion of the costs in a typical business are driven by logistic practices and the quality of SC relationships. Additionally, since logistics tend to be fixed asset intensive by nature, the desire to reduce fixed asset investment as a way to improve efficiency led to distribution networks rationalization, such as third-party logistics subcontracting and leasing instead of buying. Logistics and SC strategy are also linked to the working capital, namely long pipelines that generate more inventory, order fill and invoice accuracy that directly impact accounts receivables, and procurement policies that affect cash flow. Working capital requirements can be reduced through time reduction in the pipeline, elimination of non-value adding time in the SC, and subsequent order-to-cash cycle times (from materials procurement through the sale of finished products). Christopher and Ryals (1999), based on Srisvastava et al. (1998) suggestion of evaluating strategies in terms of how they either enhance or accelerate cash flows, argue that if the total end-to-end pipeline time can be compressed then shareholder value can be improved. This is because the shorter the pipeline the less working capital is locked up and the more responsive to demand the company can be. In conclusion, the critical objective of the supply chain should be to identify opportunities for reducing total cash-to-cash cycle time.

Lambert and Burduroglu (2000) reviewed the different methods to evaluate the value generated by logistic investments and summarized their main advantages and disadvantages. The several metrics mentioned in the literature include customer satisfaction, customer value-added (CVA), total cost analysis, segment profitability analysis, strategic profit model and shareholder value. According to the authors, despite the fact that the more satisfied customers are with a supplier, the more willing they are to buy more from that supplier, the number of firms where this occurs is small. Consequently, customer satisfaction measures as well as customer value-added measures fail to relate customer service performance and its cost with revenue generation.

Total cost analysis intends to minimize the necessary total costs of logistics, including transportation, warehousing, inventory, order processing and information systems, purchasing, and production-related costs to provide a given service level. Total cost analysis can be used to show the performance of logistics both from the top management's perspective and from customer's perspective; however, it ignores any revenue implications. Segment profitability focuses the analysis on revenue, since different customer service levels can influence customer's sales volume; thus, the firm decides to allocate its resources to those segments that are most profitable. However, total cost analysis and segment profitability analysis only measure the inventory cost and accounts receivables.

The strategic profit model demonstrates how asset management and margin management will influence return on assets, and return on net worth, which is the return on shareholders' investment plus retained earnings, offering managers the possibility to determine the overall impact of decisions with regard to cash flows and asset utilization.

Although the strategic profit model has many strengths over the methods of value measuring described, researchers on corporate finance have shown consensus that shareholder value focusing on cash flow is a better performance metric of the financial consequences of different alternative strategies and investments than traditional accounting measurements (Stern, 1990; Copeland et al., 1994; Stern et al., 1995; Christopher and Ryals, 1999).

To Copeland et al. (1994) discounted cash flows is the best measure of value because it requires a long term perspective and managers should understand how to compare cash flows from different time periods on a risk-adjusted basis. Decisions based on traditional accounting measures might improve these measures (e.g. net operating profit after taxes and net income) in the short-term, but might reduce the long-term value of the business.

According to Lambert and Burduroglu (2000) one of the most accepted lines of thought on how corporate performance relates to shareholder value is shareholder value analysis (SVA) introduced by Rappaport in 1986. To Rappaport (1986, *in* Lambert and Burduroglu, 2000) a business value is obtained by the net present value of its cash flows discounted at the appropriate cost of capital. Such a view is based on the premise that discounted cash flow principles can be applied to the business as a whole and that value is only increased if returns exceed the cost of capital. The author also identified seven key generic business value drivers: sales growth rate, operating profit margin, cash tax rate, fixed capital needs, working capital needs, cost of capital, and planning period giving managers a possibility to evaluate different strategies in value terms.

Puigjaner and Guillén (2008) SCND propose the above mentioned discounted-free-cash-flow (DCFC) method as a measure of the shareholder value to be maximized. The authors consider that maximizing shareholder value is a main priority for the firms and indeed it is what drives their decisions. The DFCF method has become the most preferred approach for valuation of companies in order to properly assessing the business value drivers and its use is gaining wider acceptance in industrial contexts.

EVA, introduced by Stern (1990), is an alternative approach to SVA. According to Stern (1990), shareholder value depends on the rate of return earned on total investor capital relative to the required rate of return, known as the "cost of capital," and the amount of investor capital tied up in the business. Shareholder value is created only when the rate of return on capital exceeds the cost of that capital. The precise amount of value added, economic value added (EVA), is equal to the amount of total capital invested multiplied by the difference between return on capital and the cost of that capital. The EVA for each period in the forecast horizon is then discounted and summed up over the whole horizon to produce a premium, which is added to the invested capital to determine the common equity value.

Lambert and Burduroglu (2000), in accordance with Stern's shareholder value approach and with Christopher and Ryals (1999) framework on how SC strategy affect shareholder value, establish how logistics affect EVA. This is illustrated in Figure 3.

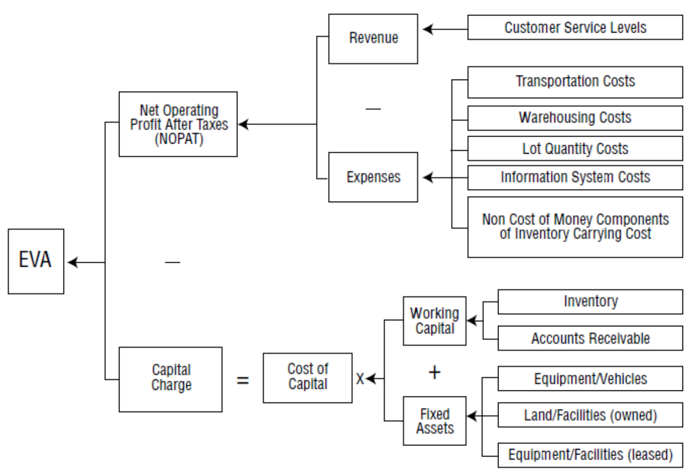

Figure 3 Logistics impacts on EVA (Lambert and Burduroglu, 2000).

Longinidis and Georgiadis (2011) chose EVA as the financial figure that expresses the company's value, following Stern (1995) approach and the works of Lovata and Costigan (2002) and Ashayeri and Lemmes (2006). However, Mills and Print (1995) preference goes for the SVA approach with its focus of attention on value drivers and on economic rather than accounting principles. EVA has many traits, which are sometimes linked to conventional accounting approaches. To Damodaran (1996), EVA has won many adopters because of its simplicity.

Recently Klibi et al. (2010) discussed relevant SCND optimization criteria and supported the idea that in order to obtain value-creating supply chains the chosen criteria should maximize the present value of all future cash flows generated by the SCN, in accordance with SVA. To these authors, this is particularly true when a multi-period finite planning horizon is considered, as opposed to a single planning period, since the timing of structural SCN decisions (opening/closing of facilities) and the consideration of real options became important issues. They also agree that static financial or operational performance indicators, such as EVA, are easy to compute from historical data and especially useful for understanding a company's performance in a single year, although the results are not so real.

2.6 Research opportunities in supply chain network design

The Garcia and You (2015) review some research opportunities and challenges in the field of supply chain design. The authors identify two areas of growing interest: enterprise-wide optimization (EWO) and energy and sustainability issues.

EWO concept was described by Grossmann (2005) as the optimization of the operations of supply, manufacturing, and distribution activities of a company in order to reduce costs and inventories. Grossmann (2005) adds that the information and the decision-making among the various functions that comprise the supply chain (purchasing, manufacturing, distribution, sales), across various geographically distributed organizations (vendors, facilities, and markets), and across various levels of decision-making (strategic, tactical, and operational) should be integrated. This can be achieved with the development of large-scale, complex, multi-scale supply chain models to explore and analyze alternatives of the supply chain to yield overall optimum economic performance, as well as high levels of customer satisfaction.

Additionally, the recent trends towards sustainable companies are also considered an opportunity to improve supply chain design. Traditionally, optimization of supply chains focused on improving the economic performance of the supply chain. However, legislative and societal pressures to improve the energy, environmental, and social performance of the companies lead to the need of re-design and/or improve of the actual supply chains to operate under environmental legislation. Nevertheless, to achieve truly sustainable solutions, a supply chain should be designed with economic, environmental, and social sustainability criteria (Garcia and You, 2015). This way, a key research challenge in this area is to develop quantitative measures and models for the three design criteria of interest, especially those without clear physical definition such as responsiveness and social sustainability.

After a comprehensive review of studies in the fields of supply chain network design from 2000 to 2015, Govindan et al. (2017) identified a list of potential issues for future research directions. One of the topics suggested is to consider the uncertainty caused by natural or man-made disruptions, since currently fewer than 20% of studies include uncertainty. According to the authors, considering reliable and resilient SC networks under disruption risks would have high potential as a future research direction. Addressing social responsibility or environmental aspects in designing supply chains networks is another research suggestion made by these authors.

We can conclude for the need of developing SCND models to address complex aspects such as the integration of the decision-making from all the organizations of the SC; to include different sources of uncertainty from real world; and to include environment aspects, as well as social responsibility, and find the right quantitative metrics.

3 Problem definition

3.1 Problem description

The purpose of our SCND problem is to determine the manufacturing and distribution network for an entire company. In particular, our model considers the design of a deterministic multiproduct, multi-echelon supply chain network problem, as shown in Figure 4, in a dynamic environment, allowing for decision making at every single time period of the planning horizon. According to Beamon (1998), dynamic models are required when dealing with the dynamic characteristics of the supply chain system, which are due to demand fluctuations, lead-time delays, sales forecasting, amongst others.

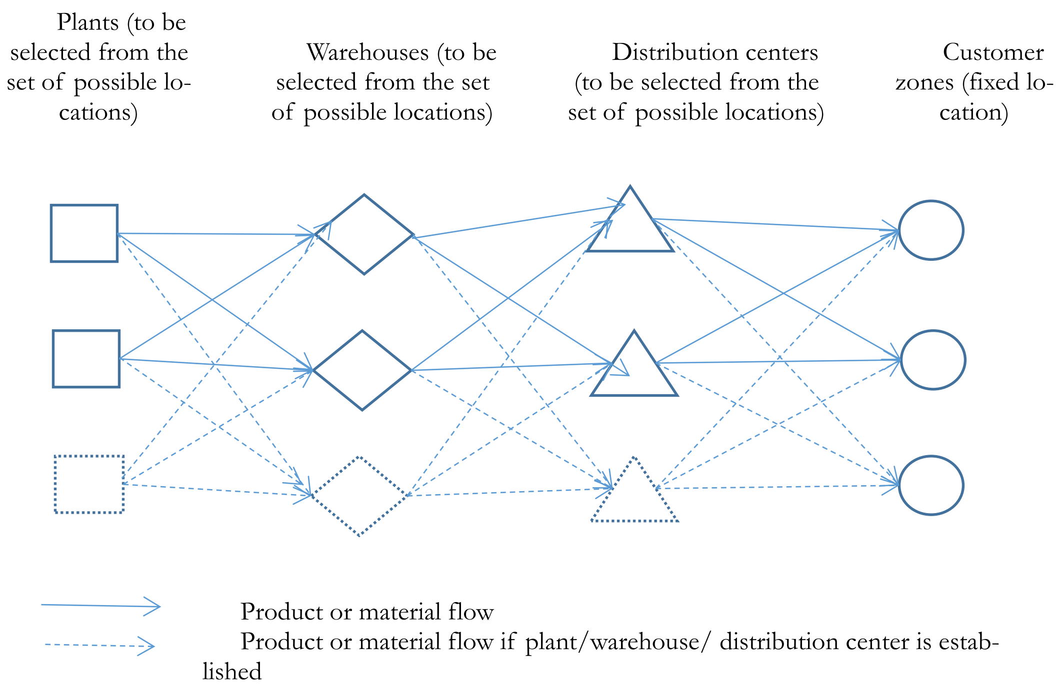

Figure 4 The supply chain network considered in the proposed model.

In an unstable economic environment, companies must decide on which assets to shut down, in times of decreasing demand, and on which to open, when market conditions improve (Dias et al., 2006; Pimentel et al., 2013), in order to increase its total value (Farahani et al., 2014). To the reengineering of an existing SCN, it is usual to elaborate an alternative potential network to compare with the existing one (Klibi et al., 2010). However, our model not only supports the design of a new SCN, but also the redesign of an existing one, either through new investments, that reflect expansion, or through disinvestments, that reflect contraction. We only found one study (Nagurney, 2010) that also proposes a model to cope with network design and redesign, however, in it two different problems are considered, one for design and another for redesign. In addition, the objective function considers only minimization of the operational (production, shipment and storage) and investment costs.

Note that, in addition to dealing with economic or other problem environment dynamics through network reconfiguration over time, we may also implement our model using a receding horizon strategy. Such a strategy encompasses the implementation of the model decisions only in the short period, while solving the problem for a longer period. By repeatedly doing so, one can adapt its network to the reality being faced at any time.

As our model integrates process operations with corporate financial decisions and constraints, the mathematical formulation merges variables and parameters belonging to each of these topics.

Operations data

- Customer base is divided into zones through geographic and marketing criteria. Demand is known for each customer zone and for each time period of the planning horizon and it must be satisfied entirely. Each customer zone is supplied by one or more distribution centers;
- Given the existing customer zones, the network is configured (or reconfigured, if the company has already been established) by deciding the establishment of plants, warehouses, and distribution centers. Any plants (if established) can produce any product, subject to a maximum production capacity, resources availability, and a minimum economic quantity of production. Warehouses and distribution centers (if established) are subject to maximum and minimum limits on material handling capacity, the former is due to facility capacity, while the latter is economically determined. Plants (if established) can supply one or more warehouses, but can only supply warehouses. Warehouses are supplied by one or more production plants and can supply one or more distribution centers. Each distribution center may supply several customer zones and can be supplied by one or more warehouses. Finally, each customer can be supplied by one or more distribution centers. There are also upper and lower limits to the quantities that can practically and economically be transferred between facilities;

- During the planning horizon, there can only be up to one opening and one closing decision for each facility; if the company is already established, each of the pre-existent facilities can be closed, however it cannot be re-opened. Note that, although this may seem to be a limitation of our approach, it is not since in a receding horizon strategy a facility may actually be opened and closed several times. As long as a certain amount of time, the strategy time window, has elapsed;
- Any decison on opening or closing a facility is taken at the beginning of the planning period and is immediatly available;
- Every facility type (plants, warehouses, and distribution centers) can carry inventory of any product at any time. As said before, each warehouse and distribution center, if established, has to held a total quantity of products that respects its maximum and minimum limits. In addition, there are also lower limits imposed on each product, i.e., safety stock, regarding each warehouse and each distribution center. Regarding plants, only inventory upper limits are imposed, however these limits are per product.

Financial data

- The configuration of the network, along with its operation, implies fixed costs and variable costs, that may be time variant. Fixed costs are associated with establishing (e.g., facilities construction, equipment, and tools acquisition) and closing facilities (e.g., dismissal costs, obsolete inventory) and with transportation routes (representing a route setup cost associated with vehicles, drivers, tools, etc.). Variable costs are associated with production (e.g., materials acquisition, staff expenses, insurance), transportation (products transportation and handling, insurance), and inventory holding (e.g. maintenance, insurance, opportunity, etc);
- The selling prices of each product are known for each time period and each customer zone;
- The cost of capital, loans interest rate, and tax rate are known for each time-period;
- The depreciation rate is known and depreciation calculation follows accounting rules, in order to calculate depreciations for each asset and time period;
- The selling price for each facility and for each time period is known, and represents the market price of each facility;
- A company growth rate in perpetuity, which is an estimate of how much the company will grow in the future, is established;

- Financial ratios are calculations based on income statements, balance sheets and cash flow statements and are used to assess the relative strength of companies. The boundaries for each of the financial ratios considered (performance ratios, efficiency ratios, liquidity ratios, and leverage ratios) and for each time period are established, in order to maintain the good financial position of the company;

Our goal is to determine:

- Strategic operation decisions regarding the facilities (plants, warehouses and distribution centers) to be established (opening or closing) in the possible given locations; and the supply routes from plants to warehouses, warehouses to distribution centers, and distribution centers to customer zones, for each time period of the planning horizon;
- Tactical operation decisions that include the amount produced of each product at each plant, the flows of materials between facilities, and the inventory levels, which include a per product safety stock at warehouse and distribution center levels and a maximum inventory at plants, and a maximum and minimum inventory of products both at the warehouses and the distribution centers;
- Financial decisions of total investment to establish the network, bank loans, and new capital entries from shareholders needed to finance the investment, as well as the amount of repayments to the bank for each time period of the planning horizon;

in order to maximize shareholder value at the end of the planning horizon for the company as a whole (and not for each facility), taking into account the operations constraints (functional and logical) and financial constraints (financial ratios, maximum borrowed amount and minimum repayments for each time period). The shareholder value will be measured by shareholder value analysis (SVA), which deducts the value of the long term liabilities from the value of the firm at the end of the planning horizon, obtained through de discounted free cash flow (DFCF) method.

3.2 Solution approach

Many practical problems can be formulated as optimization problems. Mathematical modelling is concerned with a description of various types of relations between the quantities involved in a given situation. The purpose of a mathematical programming model is to optimize a stipulated objective function subject to stipulated constraints, in order to determine the values of a set of decision variables.

Optimization using mathematical programming is probably the most used approach in supply chain management decision making (Grossman and Guillén, 2010) and models are used to optimize high-level decisions involving supply chain network design, medium term production, and distribution planning (Papageorgiou, 2009).

Mathematical programming can be linear, when the objective function and all the constraints of the problem are linear functions of the variables; or nonlinear, otherwise. If some of the variables of a linear problem are integer or belong to a discrete set, it is called a mixed integer linear programming (MILP) model (Ermoliev and Wets, 1988). Note that binary variables are a type of discrete variables that encompass information that is confined to two possible options (e.g., yes or no).

From the modelling perspective, the preferred method is mixed-integer linear programming (MILP), since it is a simple representation that avoids nonlinearities and allows problems to be easily adapted to a wide range of industrial scenarios (Grossman and Guillén, 2010). Usually, in MILP formulations, continuous variables are used to represent materials flows and sales of products, whereas binary variables are employed to model tactical and/or strategic decisions associated with the network configuration, such as establishment of facilities, selection of technologies, and establishment of transportation links. Usually these problems are solved via branch and bound techniques, sometimes complemented with other strategies such as Lagrangean, Benders and bi-level decomposition methods (Grossman and Guillén, 2010).

Our work formulates the problem described in the previous section as a MILP model, which includes discrete (binary) variables related with the facilities to be opened/closed and continuous decision variables related with quantities to produce, to transport, and to store and with financial values. The problem will be solved using the mathematical programming solver Gurobi, version 7.0.1., incorporated in Visual Studio 2015, using C++ as modelling language.

4 Mathematical programming model

In this chapter, a Mixed-Integer Linear Programming (MILP) is proposed for the problem being addressed, which was described in detail in Chapter 3. Recall that we have to decide on facilities to be established in the possible given locations, the amount of each product to be produced at each plant, the flows of products between facilities, and the inventory level of each product at each plant, each warehouse, and each distribution center. The decisions are limited by functional and logical constraints, as usual. In addition, we also have to satisfy the following financial ratios: performance ratios, liquidity ratios and leverage ratios. Amongst all possible solutions, we are interested in finding one that maximizes the company's shareholder value. Both the financial constraints and the objective function are calculated based on the works by Mills and Print (1995) and Brealey et al. (2011).

Let us first introduce the notation used.

Notation

Sets and Indices:

E	set of production resources indexed by e;
I	set of products, indexed by i;
J	set of plant locations (existing and potential), indexed by j;
K	set of distribution center locations (existing and potential), indexed by k;
L	set of customer locations, indexed by l;
M	set of warehouse locations (existing and potential), indexed by m;
$\mathcal{T}$	set of T planning periods comprising the planning horizon, indexed by s and t.

Parameters:

A^{P}_{jt}	market price of plant j at time period t, with $j \in J$ and $t \in \mathcal{T}$;
A^{W}_{mt}	market price of warehouse m at time period t, with $m \in M$ and $t \in \mathcal{T}$;
A^{D}_{kt}	market price of distribution center k at time period t, with $k \in K$ and $t \in \mathcal{T}$;
C^{P+}_{jt}	cost of establishing a plant at location j at time period t, with $j \in J$ and $t \in \mathcal{T}$;
C^{W+}_{mt}	cost of establishing a warehouse at location m at time period t, with $m \in M$, and $t \in \mathcal{T}$;
C^{D+}_{kt}	cost of establishing a distribution center at location k at time period t, with $k \in K$, and $t \in \mathcal{T}$;

C^{P-}_{jt} cost of closing a plant at location *j* at time period *t,* with $j \in J$ and $t \in \mathcal{T}$;

C^{W-}_{mt} cost of closing a warehouse at location *m* at time period *t,* with $m \in M$ and $t \in \mathcal{T}$;

C^{D-}_{kt} cost of closing a distribution center at location *k* at time period *t,* with $k \in K$ and $t \in \mathcal{T}$;

C^{FP}_{ijt} fixed production cost for product *i* at plant *j* at time period *t,* with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

C^{VPP}_{ijt} unit production cost for product *i* at plant *j* at time period *t* , with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

C^{FTPW}_{ijmt} fixed transportation cost of product *i* from plant *j* to warehouse *m* at time period *t,* with $i \in I$, $j \in J$, $m \in M$, and $t \in \mathcal{T}$;

C^{VTPW}_{ijmt} unit transportation cost of product *i* from plant *j* to warehouse *m* at time period *t,* with $i \in I$, $j \in J$, $m \in M$, and $t \in \mathcal{T}$;

C^{FTWD}_{imkt} fixed transportation cost of product *i* from warehouse *m* to distribution center *k* at time period *t,* with $i \in I$, $m \in M$, $k \in K$, and $t \in \mathcal{T}$;

C^{VTWD}_{imkt} unit transportation cost of product *i* from warehouse *m* to distribution center *k* at time period *t,* with $i \in I$, $m \in M$, $k \in K$, and $t \in \mathcal{T}$;

C^{FTDC}_{iklt} fixed transportation cost of product *i* from distribution center *k* to customer zone *l* at time period *t,* with $i \in I$, $k \in K$, $l \in L$, and $t \in \mathcal{T}$;

C^{VTDC}_{iklt} unit transportation cost of product *i* from distribution center *k* to customer zone *l* at time period *t,* with $i \in I$, $k \in K$, $l \in L$, and $t \in \mathcal{T}$;

C^{IP}_{ijt} unit inventory cost of product *i* at plant *j* at time period *t,* with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

C^{IW}_{imt} unit inventory cost of product *i* at warehouse *m* at time period *t,* with $i \in I$, $m \in M$, and $t \in \mathcal{T}$;

C^{ID}_{ikt} unit inventory cost of product *i* at distribution center *k* at time period *t,* with $i \in I$, $k \in K$, and $t \in \mathcal{T}$;

D^{max}_{k} maximum capacity of distribution center *k,* with $k \in K$;

D^{min}_{k} minimum capacity of distribution center *k,* with $k \in K$;

I^{max}_{ijt} maximum inventory level of product *i* being held at plant *j* at the end of time period *t,* with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

O_{ilt} demand of product i from customer zone *l* at time period *t,* with $i \in I$, $l \in L$, and $t \in \mathcal{T}$;

P^{max}_{ij} maximum production capacity of product *i* at plant *j*, with $i \in I$ and $j \in J$;

P^{min}_{ij} minimum production capacity of product *i* at plant *j*, with $i \in I$ and $j \in J$;

PR_{ilt} unit selling price of product *i* at customer zone *l* at time period t, with $i \in I$, $l \in L$, and $t \in \mathcal{T}$;

Q^{PW}_{jm} maximum limit of products that can be transferred from plant *j* to warehouse *m,* with $j \in J$ and $m \in M$;

Q^{WD}_{mk} maximum limit of products that can be transferred from warehouse *m* to distribution center *k,* with $m \in M$ and $k \in K$;

Q^{DC}_{kl} maximum limit of products that can be transferred from distribution center *k* to customer zone *l*, with $k \in K$ and $l \in L$;

R_{je} available quantity of resource *e* at plant *j*, with $e \in E$ and $j \in J$;

W^{max}_{m} maximum capacity of warehouse *m*, with $m \in M$;

W^{min}_{m} minimum capacity of warehouse *m* , with $m \in M$;

SS^{D}_{ikt} safety stock of product *i* at distribution center *k* at time period *t*, with $i \in I$, $k \in K$, and $t \in \mathcal{T}$;

SS^{W}_{imt} safety stock of product *i* at warehouse *m* at time period *t*, with $i \in I$, $m \in M$, and $t \in \mathcal{T}$;

CR_t lower limit of cash ratio at time period *t*, with $t \in \mathcal{T}$;

CCR_t lower limit of cash coverage ratio at time period *t*, with $t \in \mathcal{T}$;

CUR_t lower limit of current ratio at time period *t*, , with $t \in \mathcal{T}$;

CP_t upper limit of new capital entries at time period *t*, with $t \in \mathcal{T}$;

ATR_t lower limit of assets turnover ratio at time period *t*, with $t \in \mathcal{T}$;

TDR_t upper limit of total debt ratio at time period *t*, with $t \in \mathcal{T}$;

$LTDR_t$ upper limit of long-term debt ratio at time period *t*, with $t \in \mathcal{T}$;

PMR_t lower limit of profit margin ratio at time period *t*, with $t \in \mathcal{T}$;

QR_t lower limit of quick ratio at time period *t*, with $t \in \mathcal{T}$;

ROA_t lower limit of return on assets ratio at time period *t*, with $t \in \mathcal{T}$;

ROE_t lower limit of return on equity ratio at time period *t*, with $t \in \mathcal{T}$;

$ACDPR_{st}$ accumulated depreciation rate of a facility open at time period *s* and closed at time period *t*, with *s* and $t \in \mathcal{T}$;

DPR_{st} depreciation rate of a facility at the end of time period *t*, with *s* and $t \in \mathcal{T}$;

TR_t tax rate at time period *t*, with $t \in \mathcal{T}$;

IR_t long-term interest rate at time period *t*, with $t \in \mathcal{T}$;

r_t cost of capital rate at time period *t*, with $t \in \mathcal{T}$;

ϱ_{eij} coefficient of rate of utilization of resource *e* to produce product *i* in plant *j*, with $e \in E$, $i \in I$, and $j \in J$;

α_t coefficient of revenues outstanding at time period *t*, with $t \in \mathcal{T}$;

μ_t coefficient of payables outstanding at time period *t*, with $t \in \mathcal{T}$;

γ_t coefficient for loans at time period *t*, with $t \in \mathcal{T}$;

Decisions and Auxiliary Variables:

q^{P}_{ijt} inventory level of product *i* being held at plant *j* at time period *t*, with

$i \in I$, $j \in J$, and $t \in \mathcal{T}$;

q^{W}_{imt} inventory level of product i being held at warehouse m at time period t, with $i \in I$, $m \in M$, and $t \in \mathcal{T}$;

q^{D}_{ikt} inventory level of product i being held at distribution center k at time period t, with $i \in I$, $k \in K$, and $t \in \mathcal{T}$;

p_{ijt} quantity of product i produced at plant j at time period t, with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

x^{PW}_{ijmt} quantity of product i transferred from plant j to warehouse m in time period t, with $i \in I$, $j \in J$, $m \in M$, and $t \in \mathcal{T}$;

x^{WD}_{imkt} quantity of product i transferred from warehouse m to distribution center k in time period t, with $i \in I$, $m \in M$, $k \in K$, and $t \in \mathcal{T}$;

x^{DC}_{iklt} quantity of product i transferred from distribution center k to customer zone l during time period t, with $i \in I$, $k \in K$, $l \in L$, and $t \in \mathcal{T}$;

y^{P+}_{jt} 1 if a plant at location j is opened at time period t; 0 otherwise, with $j \in J$ and $t \in \mathcal{T}$;

y^{P-}_{jt} 1 if a plant at location j is closed at time period t; 0 otherwise, with $j \in J$ and $t \in \mathcal{T}$;

y^{W+}_{mt} 1 if a warehouse at location m is opened at time period t; 0 otherwise, with $m \in M$ and $t \in \mathcal{T}$;

y^{W-}_{mt} 1 if a warehouse at location m is closed at time period t, 0 otherwise, with $m \in M$ and $t \in \mathcal{T}$;

y^{D+}_{kt} 1 if a distribution center at location k is opened at time period t, 0 otherwise, with $k \in K$ and $t \in \mathcal{T}$;

y^{D-}_{kt} 1 if a distribution center at location k is closed at time period t, 0 otherwise, with $k \in K$ and $t \in \mathcal{T}$;

u_{ijt} 1 if product i is produced at plant j in time period t, 0 otherwise, with $i \in I$, $j \in J$, and $t \in \mathcal{T}$;

z^{PW}_{jmt} 1 if plant j supplies warehouse m at time period t, 0 otherwise, with $j \in J$, $m \in M$, and $t \in \mathcal{T}$;

z^{WD}_{mkt} 1 if warehouse m supplies distribution center k in time period t, 0 otherwise, with $m \in M$, $k \in K$, and $t \in \mathcal{T}$;

z^{DC}_{klt} 1 if distribution center k supplies customer zone l in time period t, 0 otherwise, with $k \in K$, $l \in L$, and $t \in \mathcal{T}$;

w^{P-}_{jst} 1 if plant j was opened at time period s and closed at time period t, 0 otherwise, with $j \in J$ and s and $t \in \mathcal{T}$;

w^{P+}_{jst} 1 if plant j was opened at time period s and is still open at time period t, 0 otherwise, with $j \in J$ and s $t \in \mathcal{T}$;

w^{W-}_{mst} 1 if warehouse m was opened at time period s and closed at time period t, 0 otherwise, with $m \in M$ and s and $t \in \mathcal{T}$;

w^{W+}_{mst} 1 if warehouse *m* was opened at time period *s* and is still open at time period *t*, 0 otherwise, with $m \in$ M and *s* and $t \in \mathcal{T}$;

w^{D-}_{kst} 1 if distribution center *k* was opened at time period *s* and closed at time period *t*, 0 otherwise, with $k \in$ K and *s* and $t \in \mathcal{T}$;

w^{D+}_{kst} 1 if distribution center *k* was opened at time period *s* and is still open at time period *t*, 0 otherwise, with $k \in$ K and *s* and $t \in \mathcal{T}$;

b_t bank loans at time period *t,* with $t \in \mathcal{T}$;

rp_t bank repayments at time period *t,* with $t \in \mathcal{T}$;

ncp_t New capital entries at time period *t,* with $t \in \mathcal{T}$;

C_t cash at time period *t,* with $t \in \mathcal{T}$;

CA_t current assets at time period *t,* with $t \in \mathcal{T}$;

CS_t cost of sales at time period *t,* with $t \in \mathcal{T}$;

DPV_t depreciation value at time period *t,* with $t \in \mathcal{T}$;

FAD_t fixed assets divestment at the time period *t,* with $t \in \mathcal{T}$;

FAI_t fixed assets investment at the time period *t,* with $t \in \mathcal{T}$;

IC_t holding inventory cost at time period *t,* with $t \in \mathcal{T}$;

IP_t interest paid (financial expenses) at time period *t,* with $t \in \mathcal{T}$;

IV_t value of inventory at time period *t,* with $t \in \mathcal{T}$;

LTD_t long term debt at time period *t,* with $t \in \mathcal{T}$;

NFA_t net fixed assets (property, plant, and equipment) at time period *t,* with $t \in \mathcal{T}$;

NOI_t non-operating income at time period *t,* with $t \in \mathcal{T}$;

PC_t production cost at the time period *t,* with $t \in \mathcal{T}$;

REV_t revenues from sales at time period *t,* with $t \in \mathcal{T}$;

TC_t transportation cost time period *t,* with $t \in \mathcal{T}$.

4.1 Objective function

As discussed in the previous chapters, supply chain strategic decisions and its operation affect corporate finances and, consequently, affect the financial value created for shareholders. We also concluded that, among the different approaches used to evaluate the value generated for shareholder, shareholder value analysis (SVA) is one of the most accepted lines of thought. In accordance with this, our work maximizes shareholder value created with the network configuration, using the SVA.

SVA computes shareholder value (or equity value) by deducting the value of the long term liabilities at the end of the lifetime of the project (LTD_T) from the value of the firm for the time period in analysis. The latter is obtained through de discounted free cash flow ($DFCF$) method thus, our objective function is given by equation (1).

$$max\, SVA = DFCF - LTD_T. \tag{1}$$

Next, we explain how these terms, $DFCF$ and LTD_T, are calculated, as well as all components involved to obtain them.

The $DFCF$ is obtained by adding the discounted terminal value of the firm (V_T) to the summation of the discounted free cash flows to the firm over the planning period ($FCFF_t$), as given by Equation (2). Recall that T represents the number of time periods of the planning horizon. The cost of capital (r_t) is the discount rate used, since it reflects the time value of money and the investment risk and thus, can be understood as the expected return required to attract funds to a particular investment.

$$DFCF = \sum_{t \in \mathcal{T}} \frac{FCFF_t}{(1+r_t)^t} + \frac{V_T}{(1+r_T)^T}, \tag{2}$$

Where V_T is the terminal value of the firm, which is the value of all future cash flows, beyond the planning horizon. In this work, V_T is calculated through the growing perpetuity model, which assumes that free cash flows grow at a constant rate (g) forever. The terminal value of the firm is obtained by dividing the free cash flow in the first period beyond the planning horizon ($FCFF_{T+1}$) by the difference between the discount rate for the last time period (r_T) and the growth rate in perpetuity (g).

$$V_T = \frac{FCFF_{T+1}}{r_T - g}, \qquad \forall t \in \mathcal{T}. \tag{3}$$

The $FCFF_{T+1}$ is estimated based on an adjustment of the FCFF from the last period of the planning horizon, making it grow at the perpetuity rate g (see Equation (4)). The adjustment in the FCFF is needed because we are assuming stability beyond the planning horizon, meaning that there will be no extraordinary gains (non-operating income is set to zero) and that new investments will be offset by depreciation.

$$FCFF_{T+1} = [(REV_T - CS_T - DPV_T)(1 - TR_T) - \Delta WC_T]\,(1 + g). \tag{4}$$

Free cash flow to the firm (FCFF)

The FCFF is the difference between the operating earnings after taxes and the investment needed to finance the activity. The free cash flow to the firm at each period ($FCFF_t$) is obtained by deducting the net fixed asset investment ($FAI_t - DPV_t$) and the changes in working capital (ΔWC_t), which represent the amount needed to support the business operations expenses, from the operating income after taxes. The latter is given by the revenue (REV_t) and the non-operating income (NOI_t), net of the cost of sales (CS_t) and depreciation (DPV_t). The calculation of the operating income after taxes does not include interest costs on debt in order to separate the analysis of the investment decision from the analysis of the financing decision (Brealey et al., 2011).

Operating earnings are a taxable income, meaning that taxes must be subtracted to get net income and the tax rate (TR_t) is selected according to current legislation. It is important to refer that although depreciations are considered a cost, since they reduce taxable income, they are not associated with a real payment (cash outflow), which means that, after adjusting operating income to taxes, they have to be added again to calculate the FCFF (see Equation (5)).

$$FCFF_t = (REV_t + NOI_t - CS_t - DPV_t)(1 - TR_t) - (FAI_t - DPV_t) - \Delta WC_t, \ \forall t \in \mathcal{T}. \tag{5}$$

Next, we will explain the free cash flow components and calculation in more detail.

Revenues

The revenues (REV_t) arise from selling goods or services to the different markets (customer zones) and are obtained by multiplying the quantities sold by the respective prices, as follows:

$$REV_t = \sum_{i \in I, l \in L} PR_{ilt}\, O_{ilt}, \qquad \forall t \in \mathcal{T}. \tag{6}$$

Non-operating income

The non-operating income (NOI_t) represents gains or losses not related to the typical activities of the firm, which include gains or losses from property or asset sales. Therefore, the non-operating income will be zero in every period for which no physical assets are sold. In this model, we assume that whenever there is a decision to close a facility, it will be sold.

The NOI_t includes three income components resulting from the sale of: i) plants, ii) warehouses, and iii) distribution centers. The gain/loss from a plant alienation is the difference between the cash inflow resulting from the sale (which is the market price of the plant for the period (A_{jt}^{P}) minus the cost of closing it (C_{jt}^{P-})) and the plant net value. The net value of a plant that was opened in time period *s* and closed in time period *t* is equal to its acquisition cost (C_{js}^{P+}) deducted by the depreciations accumulated between time periods *s* and *t* ($ACDPR_{st}$). The gains or losses of warehouses and of distribution centers sales are calculated in a similar way.

$$\begin{aligned} NOI_t = & \sum_{j\in J}(A_{jt}^{P}-C_{jt}^{P-})y_{jt}^{P-} - \sum_{S=1}^{t} C_{js}^{P+}\,(1-\ ACDPR_{st})w_{jst}^{P-} \\ & + \sum_{m\in M}(A_{mt}^{W}-C_{mt}^{W-})y_{mt}^{W-} - \sum_{S=1}^{t} C_{ms}^{W+}\,(1-\ ACDPR_{st})w_{mst}^{W-} \\ & + \sum_{k\in K}(A_{kt}^{D}-C_{kt}^{D-})y_{kt}^{D-} \sum_{S=1}^{t} C_{ks}^{D+}\,(1-\ ACDPR_{st})w_{kst}^{D-}, \qquad \forall t \in \mathcal{T}, \end{aligned} \tag{7}$$

where y_{jt}^{P-} is a binary variable assuming the value 1 if a closing decision for plant *j* is made in time period *t* and w_{jst}^{P-} is also a binary variable assuming the value 1 if the decisions of opening plant *j* at time period *s* and closing it at time period *t* are made; y_{jt}^{W-}, y_{mt}^{D-}, w_{mst}^{W-}, and w_{kst}^{D-} have similar meanings for warehouses and distribution centers, respectively.

Cost of sales

The cost of sales (CS_t) reflects all the expenses needed to produce and deliver products to customer zones. In our model it includes four components: production costs (PC_t), transportation costs

(TC_t), inventory holding costs (IC_t), and changes in inventory value ($IV_t - IV_{t-1}$), as expressed in Equation (8).

$$CS_t = PC_t + TC_t + IC_t - (IV_t - IV_{t-1}), \qquad \forall t \in \mathcal{T}. \tag{8}$$

Production costs have a variable and a fixed component, as follows:

$$PC_t = \sum_{i \in I} \sum_{j \in J} (C_{ijt}^{VPP}\, p_{ijt} + C_{ijt}^{FPP} u_{ijt}\,), \qquad \forall t \in \mathcal{T}, \tag{9}$$

where C_{ijt}^{VPP} and C_{ijt}^{FPP} represent, respectively, the variable and fixed cost associated with product *i*, plant *j*, and time period *t*. Recall that p_{ijt} is the quantity of product *i* produced in plant *j* at time period t and u_{ijt} is a binary value having the value *1* if product *i* is produced in plant *j* at time period *t* and zero otherwise.

The transportation costs, which are given by Equation (10) include three components, each having fixed and variable costs, since they are incurred when transporting products from plants to warehouses, warehouses to distribution centers, and distribution centers to customer zones. We assume these values to include the handling costs.

$$\begin{aligned} TC_t = &\sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \left(C_{ijmt}^{VTPW} x_{ijmt}^{PW} + C_{ijmt}^{FTPW} z_{jmt}^{PW} \right) \\ &+ \sum_{i \in I} \sum_{m \in M} \sum_{k \in K} (C_{imkt}^{VTWD}\, x_{imkt}^{WD} + C_{imkt}^{FTWD} z_{mkt}^{WD}) \\ &+ \sum_{i \in I} \sum_{k \in K} \sum_{l\, k\, L} \left(C_{iklt}^{VTDC} x_{iklt}^{DC} + C_{iklt}^{FTDC} z_{klt}^{DC} \right), \qquad \forall t \in \mathcal{T}. \end{aligned} \tag{10}$$

Inventory may be held at the plants, warehouses, and distribution centers. Therefore, total inventory holding costs (or storage costs) also have three components, each being proportional to the average quantity held at each facility type during the time period, as given in Equation (11).

$$IC_t = \sum_{i\in I}\sum_{j\in J}(C_{ijt}^{IP}\frac{q_{ijt}^{P} + q_{ijt-1}^{P}}{2}) + \sum_{i\in I}\sum_{m\in M}(C_{imt}^{IW}\frac{q_{imt}^{W} + q_{imt-1}^{W}}{2})$$
$$+ \sum_{i\in I}\sum_{k\in K}(C_{ikt}^{ID}\frac{q_{ikt}^{D} + q_{ikt-1}^{D}}{2}), \qquad \forall t \in \mathcal{T}. \qquad (11)$$

According to accounting rules, inventory is valued based on historic cost, in this case, the production price for each product at each time period.

$$IV_t = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{k\in K} C_{ijt}^{VPP}\left(q_{ijt}^{P} + q_{imt}^{W} + q_{ikt}^{D}\right), \qquad \forall t \in \mathcal{T}. \qquad (12)$$

Depreciation

The value of fixed assets (like plants, warehouses, and distribution centers) must be adjusted for depreciation, based on the current legislation. The total depreciated value at time period *t* (DPV_t) is expressed as the sum of the depreciated value of plants, warehouses, and distribution centers that are operating during time period *t*. In this model, we assume that fixed assets existing before the planning horizon have been completely depreciated.

$$DPV_t = \sum_{j\in J}\sum_{s=1}^{t} DPR_{st}\, C_{js}^{P+}\, w_{jst}^{P+} + \sum_{m\in M}\sum_{s=1}^{t} DPR_{st}\, C_{ms}^{W+}\, w_{mst}^{W+}$$
$$+ \sum_{k\in K}\sum_{s=1}^{t} DPR_{st}\, C_{ks}^{D+}\, w_{kst}^{W+}, \qquad \forall t \in \mathcal{T}, \qquad (13)$$

where w_{jst}^{P+}, w_{mst}^{W+}, and w_{kst}^{W+} are binary variables set to 1 if a facility (plant, warehouse, and distribution center, respectively) opened at time period *s* is still open at time period *t*.

Fixed assets investment

Fixed assets are long-term tangible assets that a firm owns and uses to conduct its business. In our model, fixed assets investment (FAI_t) at time period *t* is the value needed to finance the establishment of plants, warehouses, and distribution centers in time period *t*:

$$FAI_t = \sum_{j \in J} C_{jt}^{P+} y_{jt}^{P+} + \sum_{m \in M} C_{mt}^{W+} y_{mt}^{W+} + \sum_{kk \in K} C_{kt}^{D+} y_{kt}^{D+}, \quad \forall t \in \mathcal{T}. \tag{14}$$

Changes in working capital

The changes in working capital (ΔWC_t) are obtained by the difference between the working capital in two consecutive periods. The working capital is obtained by adding accounts receivable to inventory value and subtracting accounts payable. We assume that, at the end of time period *t*, the accounts receivable and the accounts payable are a portion of the revenues and of the operational costs, respectivly. Therefore, ΔWC_t can be written as follows:

$$\Delta WC_t = (\alpha_t REV_t - \alpha_{t-1} REV_{t-1}) + (IV_t - IV_{t-1}) - [\mu_t (PC_t + TC_t + IC_t) - \mu_{t-1}(PC_{t-1} + TC_{t-1} + IC_{t-1})], \quad \forall t \in \mathcal{T}, \tag{15}$$

where α_t and μ_t represent, respectively, the amount (in percentage) of revenues and payments outstanding in the current time period and are defined by the company policy on receivables and payables.

Long-term liabilities calculation

Long term (or non-current) liabilities are mainly represented by long-term debt (LTD_t), which is incurred to finance fixed assets investments. LTD_t is a function of the previous period debt value and current period loans (B_t) and bank repayments (RP_t), as given by Equation (16).

$$LTD_t = LTD_{t-1} + B_t - RP_t, \quad \forall t \in \mathcal{T}. \tag{16}$$

4.2 Constraints

The constraints of the model can be divided into two major groups. The first group models the financial constraints, while the second one concerns the process operations and includes strategic or structural constraints - opening/closing facilities at the possible/existing locations; and tactical constraints - quantities to be produced at the plants and transported between facilities and inventory levels.

4.2.1 Financial constraints

Financial ratios are a useful section of financial statements and provide standardized measures of a firm's performance, efficiency, leverage, and liquidity. This work uses the categories defined by Brealey et al. (2011) for these ratios and sets minimum and/or maximum threshold value for them.

4.2.1.1 Performance ratios

Performance ratios measure the financial performance and current standing of the company. This work considers two common measures, namely: return on equity (ROE) and return on assets (ROA) and for each of these ratios and each time period minimum values of ROE_t and ROA_t have to be satisfied.

Return on equity (ROE)

ROE represents the marginal investment income of shareholders. It is calculated by dividing the net income by the equity. The net income (NI) is the final result of the business, and can be obtained by subtracting the interests cost from the operating earnings, usually named EBIT (earnings before interests and taxes) in financial language, and adjusting for taxes. $EBIT_t$ and NI_t are calculated in equations (17) and (18), respectively:

$$EBIT_t = REV_t + NOI_t - CS_t - DPV_t, \qquad \forall t \in \mathcal{T}, \tag{17}$$

$$NI_t = (EBIT_t - IR_t * LTD_t)(1 - TR_t), \qquad \forall t \in \mathcal{T}. \tag{18}$$

Equity (E_t) is the residual claim or interest of the investors in assets. In our model, it is composed of the company issued capital, net income of the period, retained earnings from previous periods, and new capital entries from company partners (NCP_t). Retained earnings are the amount of net income from previous periods that stays in the company. Since in our model we assume that all the profits stay in the company (there is no dividend distribution during the planning horizon, in order to finance new projects), E_t can be calculated as follows:

$$E_t = E_{t-1} + (EBIT_t - IR_t * LTD_t)(1 - TR_t) + NCP_t, \qquad \forall t \in \mathcal{T}, \tag{19}$$

According to previous explanations, the ROE constraint can be written as:

$$\frac{(EBIT_t - IR_t * LTD_t)(1 - TR_t)}{E_t} \geq ROE_t, \qquad \forall t \in \mathcal{T}. \tag{20}$$

Return on assets (ROA)

ROA is the marginal income available to debt and equity investors from the firm's total assets. It is calculated dividing the net operating profit after taxes (NOPAT), which is calculated by deducting interests and taxes from EBIT, by the total value of the assets, the latter being given by the sum of the net fixed assets (NFA_t) and the current assets (CA_t).

$$\frac{EBIT_t(1 - TR_t)}{NFA_t + CA_t} \geq ROA_t, \qquad \forall t \in \mathcal{T}, \tag{21}$$

The current net fixed assets NFA_t are obtained from those of the previous period, which are increased/decreased in an amount equal to the value of the investment (FAI_t) /divestment (FAD_t) in fixed assets net of depreciations in time period *t*, as follows:

$$NFA_t = NFA_{t-1} + FAI_t - FAD_t - DPV_t, \qquad \forall t \in \mathcal{T}, \tag{22}$$

Investment represents fixed assets acquisitions, while divestment represents fixed assets sales. Since we assume that assets existing prior to the planning horizon were completely depreciated, FAD_t represents the net value (accounting value of the asset after depreciation) of the assets bought during the planning horizon and until time period *t*:

$$FAD_t = \sum_{s=1}^{t}\left[\sum_{j \in J} C_{js}^{P+}(1 - ACDPR_{st})w_{jst}^{P-} + \sum_{m \in M} C_{ms}^{W+}(1 - ACDPR_{st})w_{mst}^{W-} + \sum_{k \in K} C_{ks}^{D+}(1 - ACDPR_{st})w_{kst}^{D-}\right], \qquad \forall t \in \mathcal{T}, \tag{23}$$

DPV_t and FAI_t have already been defined, see equations (13) and (14), respectively.

Current assets (CA_t) include the typical items: cash and banks (C_t); accounts receivable, here represented as a percent of the revenues ($\alpha_t REV_t$), and inventory value (IV_t):

$$CA_t = C_t + \alpha_t REV_t + IV_t, \qquad \forall t \in \mathcal{T}, \tag{24}$$

Cash in each period is a function of the available cash in the previous period, the cash inflows, and the cash outflows. Cash inflows may come from: i) customer receivables and product sales, here represented as $\alpha_{t-1}REV_{t-1}$ and $(1 - \alpha_t)REV_t$, respectively; ii) fixed assets sales; iii) new capital entries (NCP_t); and iv) loans of the period to finance investments (B_t). Cash outflows may be: i) repayments of debt to the bank (RP_t); ii) interests costs, which are calculated by multiplying an interest rate by the debt of the period ($IR_t LTD_t$); iii) accounts payable and payments to suppliers, here represented as $\mu_{t-1}(PC_{t-1} + TC_{t-1} + IC_{t-1})$ and $(1 - \mu_t)(PC_t + TC_t + IC_t)$ respectively; iv) payment of income taxes of the previous period; and v) the amount invested in new assets (FAI_t).

$$C_t = C_{t-1} + \alpha_{t-1}REV_{t-1} + (1 - \alpha_t)REV_t + \left[\sum_{j \in J}(A_{jt}^{P} - C_{jt}^{P-})y_{jt}^{P-} + \sum_{m \in M}(A_{mt}^{W} - C_{mt}^{W-})\,y_{mt}^{W-} + \sum_{k \in K}(A_{kt}^{D} - C_{kt}^{D-})y_{kt}^{D-}\right] + NCP_t + B_t - RP_t - IR_t LTD_t - \mu_{t-1}(PC_{t-1} + TC_{t-1} + IC_{t-1}) - (1 - \mu_t)(PC_t + TC_t + IC_t) - TR_{t-1}(EBIT_{t-1} - IR_{t-1}LTD_{t-1}) - FAI_t, \qquad \forall t \in \mathcal{T}, \tag{25}$$

where REV_t is as defined in Equation (6). Note that income taxes are due only if there is a taxable income, that is if the EBIT net of the interest costs is positive.

4.2.1.2 Efficiency ratios

Efficiency ratios measure how well the company uses its many type of assets. The following ratios allow the company to evaluate its efficiency:

Profit margin (PMR)

PMR measures the proportion of sales that finds its way into profits. It is defined as the ratio of net income to sales revenue and must attain a minimum value at each time period (PMR_t):

$$\frac{(EBIT_t - IR_t LTD_t)\,(1-TR_t)}{REV_t} \geq PMR_t, \qquad \forall t \in \mathcal{T}. \qquad (26)$$

Asset turnover (ATR)

ATR shows the revenues generated per monetary unit of total assets, measuring how hard the firm's assets are working. It is given by the ratio of sales revenue to total assets at time period *t*:

$$\frac{REV_t}{NFA_t + CA_t} \geq ATR_t, \qquad \forall t \in \mathcal{T}. \qquad (27)$$

4.2.1.3 Liquidity ratios

Liquidity ratios are metrics used to determine how quickly and cheaply assets can be converted into cash. The ratios analysis helps the company to evaluate its ability to keep more liquid assets.

Current ratio (CUR)

CUR is the ratio of current assets to its current liabilities (or short term debt) and must attain a minimum value (CUR_t).

$$\frac{CA_t}{STD_t} \geq CUR_t, \qquad \forall t \in \mathcal{T}. \qquad (28)$$

As in our model short term loans are negligible; thus, short term debt (STD_t) is due to accounts payables and taxes, as follows:

$$STD_t = \mu_t(PC_t + TC_t + IC_t) + (EBIT_t - IR_tLTD_t)TR_t, \qquad \forall t \in \mathcal{T}. \tag{29}$$

Quick ratio (QR)

QR is the ratio of current assets (except inventory) to its current liabilities (or short term debt), which must satisfy a threshold value (QR_t) as follows:

$$\frac{C_t + \alpha_t REV_t}{STD_t} \geq QR_t, \qquad \forall t \in \mathcal{T}. \tag{30}$$

Cash ratio (CR)

CR is the ratio of cash to its current liabilities, which must satisfy a threshold value (CR_t) as follows:

$$\frac{C_t}{STD_t} \geq CR_t, \qquad \forall t \in \mathcal{T}. \tag{31}$$

4.2.1.4 Leverage ratios

Leverage ratios assess the firm's ability to meet financial obligations.

Long term debt to equity ratio (LTDR)

LTDR provides an indication on how much debt a company is using to finance its assets and is calculated by dividing long term debt (LTD_t) by equity (E_t), which have been defined in equations (16) and (19), respectively. This ratio must be below a given limit:

$$\frac{LTD_t}{E_t} \leq LTDR_t, \qquad \forall t \in \mathcal{T}. \tag{32}$$

Total debt ratio (TDR)

TDR provides an indication on the total amount of debt relative to assets, it is calculated by dividing total debt by total assets, and must be below a given limit:

$$\frac{STD_t + LTD_t}{NFA_t + CA_t} \leq TDR_t, \qquad \forall t \in \mathcal{T}. \tag{33}$$

Cash coverage ratio (CCR)

CCR measures the firm's capacity to meet interest payments in cash; thus, CCR must satisfy a given lower limit:

$$\frac{EBIT_t + DPR_t}{IR_t LTD_t} \geq CCR_t, \qquad \forall t \in \mathcal{T}. \tag{34}$$

4.2.1.5 Other financial constraints

Company partners invest in new projects in the expectation of valuing their stocks. However, new capital entries (NCP_t) are limited to the amount that partners want to invest in the company:

$$NCP_t \leq CP_t, \qquad \forall t \in \mathcal{T}. \tag{35}$$

Usually, banks impose the repayments (RP_t) to be at least the interest costs, to prevent an ever-increasing debt, that is:

$$RP_t \geq IR_t LTD_t, \qquad \forall t \in \mathcal{T}, \tag{36}$$

In addition, since repayments (RP_t) are part of the debt, in each period they must satisfy constraint (37).

$$RP_t \leq LTD_t, \qquad \forall t \in \mathcal{T}. \tag{37}$$

The company can limit the amount borrowed to a percentage of the value of investments for each time period, as follows:

$$B_t \leq \gamma_t FAI_t, \qquad \forall t \in \mathcal{T}. \tag{38}$$

4.2.2 Operations constraints

4.2.2.1 At the plant level

Production constraints force the production quantities in each plant for each product and time period to be within a pre-specified range (constraints (39) and (40)), which, in addition, are collectively limited by the available quantity of each resource in each plant and time period (constraint (41)). Recall that the availability of resources is constant overtime.

$$p_{ijt} \leq P_{ij}^{max} \sum_{s=0}^{t} w_{jst}^{P+}, \qquad \forall i \in I, j \in J, and\ t \in \mathcal{T}, \qquad (39)$$

$$p_{ijt} \geq P_{ij}^{min} \sum_{s=0}^{t} w_{jst}^{P+}, \qquad \forall i \in I, j \in J, and\ t \in \mathcal{T}, \qquad (40)$$

$$\sum_{i \in I} \rho_{ije}\, p_{ijt} \leq R_{je}, \qquad \forall j \in J, e \in E, and\ t \in \mathcal{T}. \qquad (41)$$

Since there is a fixed production cost component, we need a variable (u_{ijt}) to signal the existence of production, that is, a binary variable that assumes the value 1 whenever some non-zero quantity is produced. This is accomplished by constraints (42):

$$p_{ijt} \leq M u_{ijt}, \qquad \forall i \in I, j \in J, and\ t \in \mathcal{T}. \qquad (42)$$

Operational plants may send the products, all or part, for established warehouses as stated by constraints (43) and (44). The total quantity sent by each plant to each warehouse in each time period, if any, must satisfy the transport capacity, which is enforced by constraints (45).

$$\sum_{i \in I} \sum_{m \in M} x_{ijmt}^{PW} \leq M \sum_{s=0}^{t} w_{jst}^{P+}, \qquad \forall\ j \in J\ and\ t \in \mathcal{T}, \qquad (43)$$

$$\sum_{i \in I} \sum_{j \in J} x_{ijmt}^{PW} \leq M \sum_{s=0}^{t} w_{mst}^{W+}, \qquad \forall\, m \in M \text{ and } t \in \mathcal{T}, \qquad (44)$$

$$\sum_{i \in I} x_{ijmt}^{PW} \leq Q_{jm}^{PW} . z_{jmt}^{PW}, \qquad \forall j \in J, m \in M, \text{and } t \in \mathcal{T}, \quad (45)$$

where M is a sufficiently large number.

Inventories at the plants satisfy flow conservation constraints, thus, for each plant and each product in each time period the available inventory is determined by the inventory available in the previous period, plus the quantity produced in the current period minus the quantity sent to warehouses (see equation (46). Moreover, plant inventory is limited and, in each plant, the limits are imposed to each product and time period, see constraints (47).

$$q_{ijt}^{P} = q_{ijt-1}^{P} + p_{ijt} - \sum_{m \in M} x_{ijmt}^{PW}, \qquad \forall i \in I, j \in J, \text{and } t \in \mathcal{T}, \qquad (46)$$

$$q_{ijt}^{P} \leq I_{ijt}^{max}, \qquad \forall i \in I, j \in J, \text{and } t \in \mathcal{T}. \qquad (47)$$

Finally, we need to establish the correctness of the opening and closing decisions, as well as the correct relation with the auxiliary variables associated with the closing / remaining open status of the facilities.

A plant can only be opened at most once during the whole planning period, if it was not initially open (constraints (48)); a plant can be closed at most once (constraints (49)) if it was opened before (constraints (50)); a plant cannot be opened and closed in the same time period (constraints (51)). If a plant was opened in time period *s* and closed in time period *t*, then the opening (y_{js}^{P+}), closing (y_{jt}^{P-}), and closing status (w_{jst}^{P-}) decision variables must all be set to 1 (constraints (52)); a closing status variable is set to 1 if and only a closing decision was made (constraints (53)); an opening status variable (w_{jst}^{P+}) is set to 1 if and only an opening decision was made (constraints (54)); if a plant was opened in time period *s* and is still open in time period *t, then* there could not have been a closing decision in any of the periods in the internal *s+1* and *t* (constraints (55)).

$$\sum_{t \in \mathcal{T}} y_{jt}^{P+} \leq 1, \qquad \forall j \in J, \qquad (48)$$

$$\sum_{t \in \mathcal{T}} y_{jt}^{P-} \leq 1, \qquad \forall j \in J, \qquad (49)$$

$$y_{jt}^{P-} \leq \sum_{s=0}^{t-1} y_{js}^{P+}, \qquad \forall j \in J \; and \; t \in \mathcal{T}, \qquad (50)$$

$$y_{jt}^{P+} + y_{jt}^{P-} \leq 1, \qquad \forall j \in J and \; t \in \mathcal{T}, \qquad (51)$$

$$y_{js}^{P+} + y_{jt}^{P-} \leq w_{jst}^{P-} + 1, \qquad \forall j \in J, s = 0, \ldots \mathcal{T} - 1, and \; t = s + 1, \ldots \mathcal{T}, \qquad (52)$$

$$w_{jst}^{P-} \leq y_{jt}^{P-}, \qquad \forall j \in J, s = 0, \ldots \mathcal{T} - 1, and \; t = s + 1, \ldots \mathcal{T}, \qquad (53)$$

$$w_{jst}^{P+} \leq y_{js}^{P+}, \qquad \forall \, j \in J, \; s \in \mathcal{T}, and \; t = s, \ldots \mathcal{T}, \qquad (54)$$

$$w_{jst}^{P+} - y_{js}^{P+} + \sum_{v=s+1}^{t} y_{jv}^{P-} <= 0, \qquad \forall \, j \in J, s = 0, \ldots \mathcal{T} - 1, and \; t = s + 1, \ldots \mathcal{T}. \qquad (55)$$

4.2.2.2 At the warehouse level

Capacity constraints force the stored quantities in each warehouse for each product and time period to be within a pre-specified range (constraints (56) and (57)).

$$\sum_{i \in I} q_{imt}^{W} \leq W_m^{max} \sum_{s=0}^{t} w_{mst}^{W+}, \qquad \forall\, m \in M \text{ and } t \in \mathcal{T}, \qquad (56)$$

$$\sum_{i} q_{imt}^{W} \geq W_m^{min} \sum_{s=0}^{t} w_{mst}^{W+}, \qquad \forall\, m \in M \text{ and } t \in \mathcal{T}, \qquad (57)$$

Warehouses in operation may send the products, all or part, for distribution centers in operation as stated by constraints (58) and (59). The total quantity sent by each warehouse to each distribution center in each time period, if any, must satisfy the transport capacity, which is enforced by constraint (60).

$$\sum_{i \in I} \sum_{k \in K} x_{imkt}^{WD} \leq M \sum_{s=0}^{t} w_{mst}^{W+}, \qquad \forall m \in M \text{ and } t \in \mathcal{T}, \qquad (58)$$

$$\sum_{i \in I} \sum_{m \in M} x_{imkt}^{WD} \leq M \sum_{s=0}^{t} w_{kst}^{D+}, \qquad \forall k \in K \text{ and } t \in \mathcal{T}, \qquad (59)$$

$$\sum_{i \in I} x_{imkt}^{WD} \leq Q_{mk}^{WD} z_{mkt}^{WD}, \qquad \forall m \in M, k \in K, \text{and } t \in \mathcal{T}, (60)$$

where M is, as usual, a sufficiently large number.

As was the case for plants, inventories at the warehouses satisfy flow conservation constraints, thus, for each warehouse and each product in each time period the available inventory is determined by the inventory available in the previous period, plus the quantity received (from the plants) in the current period minus the quantity sent to distribution centers (see Equation (61)). Moreover, a safety stock is defined for each product and time period at each warehouse (see Equation (62)).

$$q_{imt}^{W} = q_{imt-1}^{W} + \sum_{j \in J} x_{ijmt}^{PW} - \sum_{k \in K} x_{imkt}^{WD}, \qquad \forall i \in I, m \in M, \text{and } t \in \mathcal{T}, \quad (61)$$

$$q_{imt}^{W} \geq SS_{imt}^{w} \sum_{s=0}^{t} w_{mst}^{W+}, \qquad \forall i \in I, m \in M, and\ t \in \mathcal{T}. \qquad (62)$$

Finally, we also need to establish the correctness of the opening and closing decisions, as well as the correct relation with the auxiliary variables associated with the closing / remaining open status of the warehouses.

A warehouse can only be opened at most once during the whole planning period, if it was not initially open (constraints (63)); a warehouse can be closed at most once (constraints (64)) if it was opened before (constraints (65)); a warehouse cannot be opened and closed in the same time period (constraints (66)). If a warehouse was opened in time period *s* and closed in time period *t*, then the opening (y_{ms}^{W+}), closing (y_{mt}^{W-}), and closing status (w_{mst}^{W-}) decision variables must all be set to 1 (constraints (67)); a closing status variable is set to 1 if and only a closing decision was made (constraints (68)); a remaining open status variable (w_{mst}^{W+}) is set to 1 if and only an opening decision was made (constraints (69)); if a warehouse was opened in time period *s* and is still opened in time period *t*, then there could not have been a closing decision in any time period in the internal *s+1* and *t* (constraints (70)).

$$\sum_{t \in \mathcal{T}} y_{mt}^{W+} \leq 1, \qquad \forall\, m \in M, \qquad (63)$$

$$\sum_{t \in \mathcal{T}} y_{mt}^{W-} \leq 1, \qquad \forall\, m \in M, \qquad (64)$$

$$y_{mt}^{W-} \leq \sum_{s=0}^{t-1} y_{ms}^{W+}, \qquad \forall\, m \in M\ and\ t \in \mathcal{T}, \qquad (65)$$

$$y_{mt}^{W+} + y_{mt}^{W-} \leq 1, \qquad \forall\, m \in M\ and\ t \in \mathcal{T}, \qquad (66)$$

$$y_{ms}^{W+} + y_{mt}^{W-} \leq w_{mst}^{W-} + 1, \qquad \forall\, m \in M, s = 0, \ldots \mathcal{T} - 1, and\ \ t = s+1, \ldots \mathcal{T}, \qquad (67)$$

$$w_{mst}^{W-} \leq y_{mt}^{W-}, \qquad \forall\, m \in M, s = 0, \ldots \mathcal{T}-1, and\;\; t = s+1, \ldots \mathcal{T}, \quad (68)$$

$$w_{mst}^{W+} \leq y_{ms}^{W+}, \qquad \forall\, m \in M, s \in \mathcal{T}, and\;\; t = s+1, \ldots \mathcal{T}, \quad (69)$$

$$w_{mst}^{W+} - y_{ms}^{W+} + \sum_{v=s+1}^{t} y_{mv}^{W-} <= 0, \qquad \forall\, m \in M, s = 0, \ldots \mathcal{T}-1, and\;\; t = s+1, \ldots \mathcal{T}. \quad (70)$$

4.2.2.3 At the distribution center level

Capacity constraints force the stored quantities in each distribution center for each product and time period to be within a pre-specified range (constraints (71) and (72)).

$$\sum_{i\,\in\, I} q_{ikt}^{D} \leq D_k^{max} \sum_{s=0}^{t} w_{kst}^{D+}, \qquad \forall\, k \in K\; and\; t \in \mathcal{T}, \quad (71)$$

$$\sum_{i\,\in\, I} q_{ikt}^{D} \geq D_k^{min} \sum_{s=0}^{t} w_{kst}^{D+}, \qquad \forall\, k \in K\; and\; t \in \mathcal{T}. \quad (72)$$

Operational distribution centers may send the products, all or part, for customer zones as stated by constraints (73). The total quantity sent by each distribution center to customer zone in each time period, if any, must satisfy the transport capacity, which is enforced by constraints (74). Assuming that customer zones do not hold inventory, the total flow of each product received by each customer zone from the distribution centers has to be equal to the corresponding market demand (see constraints (75)).

$$\sum_{i\,\in\, I} \sum_{l\,\in\, L} x_{iklt}^{DC} \leq M \sum_{s=0}^{t} w_{kst}^{D+}, \qquad \forall\, k \in K\; and\; t \in \mathcal{T}, \quad (73)$$

$$\sum_{i\,\in\, I} x_{iklt}^{DC} \leq Q_{kl}^{DC}\, z_{klt}^{DC}, \qquad \forall\, k \in K, l\; \in L, and\; t \in \mathcal{T}, \quad (74)$$

$$\sum_{k \in K} x_{iklt}^{DC} = O_{ilt}, \qquad \forall i \in I, l \in L, and\ t \in \mathcal{T}, \qquad (75)$$

where M is, as usual, a sufficiently large number.

As was the case for plants and warehouses, inventories at the distribution centers must satisfy flow conservation constraints, thus, for each distribution center and each product in each time period the available inventory is determined by the inventory available in the previous period, plus the quantity received from the warehouses minus the quantity sent to the customer zones (see Equality (76)). Moreover, a safety stock is defined for each product and time period, at each warehouse (see Equation (77)).

$$q_{ikt}^{D} = q_{ikt-1}^{D} + \sum_{m \in M} x_{imkt}^{WD} - \sum_{k \in K} x_{iklt}^{DC}, \qquad \forall i \in I, m \in M, and\ t \in \mathcal{T}, \qquad (76)$$

$$q_{ikt}^{D} \geq SS_{ikt}^{D}, \qquad \forall i \in I, m \in M, k \in K, and\ t \in \mathcal{T}. \qquad (77)$$

Finally, we also need to establish the correctness of the opening and closing decisions, as well as the correct relation with the auxiliary variables associated with the closing / remaining open status of the distribution centers.

A distribution center can only be opened at most once during the whole planning period, if it was not initially open (constraints (78)); a distribution center can be closed at most once (constraints (79)) if it was opened before (constraints (80)); a distribution center cannot be opened and closed in the same time period (constraints (81)). If a distribution center was opened in time period *s* and closed in time period *t*, then the opening (y_{ks}^{D+}), closing (y_{kt}^{D-}), and closing status (w_{kst}^{D-}) decision variables must all be set to 1 (constraints (82)); a closing status variable is set to 1 only if a closing decision was made (constraints (83)); a remaining open status variable (w_{kst}^{D+}) is set to 1 if and only an opening decision was made (constraints (84)); if a distribution center was opened in time period *s* and is still opened in time period *t*, then there could not have been a closing decision in any of the periods in the internal *s+1* and *t* (constraint (85)).

$$\sum_{t \in \mathcal{T}} y_{kt}^{D+} \leq 1, \qquad \forall\, k \in K, \qquad (78)$$

$$\sum_{t \in \mathcal{T}} y_{kt}^{D-} \leq 1, \qquad \forall\, k \in K, \qquad (79)$$

$$y_{kt}^{D-} \leq \sum\nolimits_{s=0}^{t-1} y_{ks}^{D+}, \qquad \forall\, k \in K \text{ and } t \in \mathcal{T}, \qquad (80)$$

$$y_{kt}^{D+} + y_{kt}^{D-} \leq 1, \qquad \forall\, k \in K \text{ and } t \in \mathcal{T}, \qquad (81)$$

$$y_{ks}^{D+} + y_{kt}^{D-} \leq w_{kst}^{D-} + 1, \qquad \forall\, k \in K, s = 0, \ldots \mathcal{T} - 1, \text{and } t = s + 1, \ldots \mathcal{T}, \qquad (82)$$

$$w_{kst}^{D-} \leq y_{kt}^{D-}, \qquad \forall\, k \in K, s = 0, \ldots \mathcal{T} - 1, \text{and } t = s + 1, \ldots \mathcal{T}, \qquad (83)$$

$$w_{kst}^{D+} \leq y_{ks}^{D+}, \qquad \forall\, k \in K, s = 1, \ldots \mathcal{T}, \text{and } t = s, \ldots \mathcal{T}, \qquad (84)$$

$$w_{kst}^{D+} - y_{ks}^{D+} + \sum_{v=s+1}^{t} y_{kv}^{D-} <= 0\,, \qquad \forall\, k \in K, s = 0, \ldots \mathcal{T} - 1, \text{and } t = s + 1, \ldots \mathcal{T}. \qquad (85)$$

5 Computational experiments

5.1 Case study description

The model proposed in this work is tested on the case study used by Longinidis and Georgiadis (2011), since the authors gently provided all the data (see Appendix 1 for detailed data).

Company Alpha already exists and currently has three plants (P1, P2, and P3), but holds no warehouses or distribution centers and has identified four potential locations for the former (W1, W2, W3, and W4) and six for the latter (DC1, DC2, DC3, DC4, DC5, and DC6), as it can be seen in Figure 5.

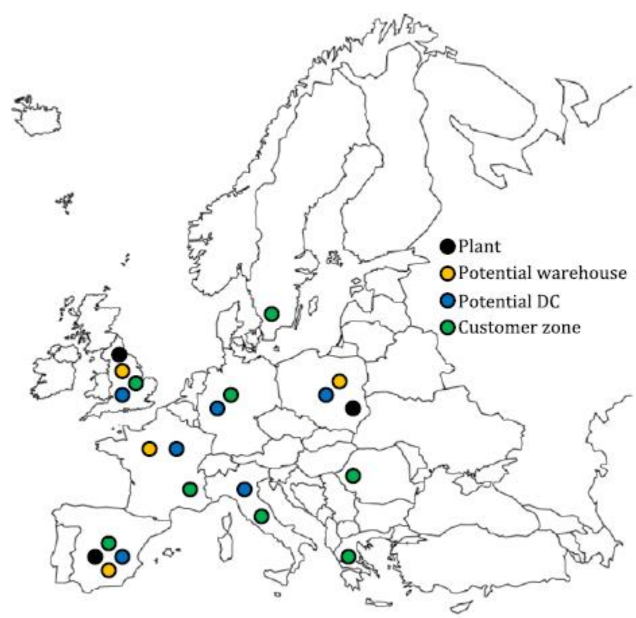

Figure 5 The possible locations for the network of the case study.

Each plant is able to produce six of the seven products within its production capacity limits (lower production limits are assumed to be zero) and holds as initial inventories the maximum production capacity of the plant (see Table 5). Note that these initial inventories are exceptionally high, about two times the average annual demand (slightly above 3000 units, see Table 6), and will, obviously, influence the model results.

	Plants		
	PL1	**PL2**	**PL3**
Initial inventory	7093	6121	3729

Table 5 Inventory quantities by plant at the beginning of the planning horizon.

	Customer zone								
	CZ1	CZ2	CZ3	CZ4	CZ5	**CZ6**	**CZ7**	**CZ8**	**Total**
year 1	337	377	404	501	310	354	360	386	3029
year 2	338	379	406	503	310	354	360	386	3036
year 3	338	381	407	504	309	354	361	386	3040
year 4	338	379	413	510	310	354	362	386	3052
Total	1351	1516	1630	2018	1239	1416	1443	1544	12157

Table 6 Demand by customer zone and in each time period.

Variable costs at the plants are incurred with production, storage, and with transportation (and handling) to the warehouses. It is important to mention that unitary transportation and handling costs from PL1, PL2, and PL3 to W1, W2, and W3, respectively, from W1, W2, and W3 to DC1, DC2, and DC3, respectively, and from DC1 and DC2 to CZ1 and CZ2, respectively, are very low compared to those of the other possible routes (the marginal transportation cost of this route is, at most, 8% of the marginal transportation cost of the other possible routes).

All warehouses and all distribution centers have a minimum and a maximum handling capacity for each time period, as well as a minimum quantity that can be economically transported to each distribution center and customer zone.

There is also a requirement of an annual safety stock for each product at each facility, equal to the total quantity transferred from the facility during a period of 15 days.

Selling price and demand for each of the seven products and each of the eight customer zones (CZ1 through to CZ8) are known. This specific case study considers a 4-years planning horizon.

We evaluated the model in different experiments in order to show the improvements of our model in relation to the original work of Longinidis and Georgiadis (2011). In the first set of experiments, we used the objective function of Longinidis and Georgiadis (2011), while in the second set we used the objective function proposed in this work. All the experiments were conducted using Gurobi 7.0.1 solver incorporated in Visual Studio 15.0.

5.2 Modelling with EVA as the objective function

This first set of experiments was designed with the aim of validating our model and showing the advantage of incorporating additional decisions in the model, as well as more accurate calculation of financial figures. Therefore, in this set of experiments we use the objective function proposed by Longinidis and Georgiadis (2011) in order to better compare the advantages and implications of our improved and enriched model. Longinidis and Georgiadis (2011) work maximizes the firm's value through the EVA (Economic Value Added) method and determines an optimal network for a given company. The decisions to be made include the number, location, and capacity of warehouses and distribution centers to be set up, flows of materials in the network, production at plants, and inventory levels at each warehouse and distribution center. All decisions are made at the beginning of each period the planning horizon.

5.2.1 EVA base-case

A first experiment is conducted in order to establish the base-case. Note that the model proposed by Longinidis and Georgiadis (2011) cannot be directly used to do so, since in addition to some inconsistencies and discrepancies in the data, there are some missing data. We have identified the following inconsistencies: i) the relation between variables Receivable Accounts and New Receivable Accounts, and the relation between variables Cash and New Cash are inexistent; and ii) the demand data provided by the authors are different from the data presented in the paper. In addition, important information is missing, such as the state of depreciation of previous assets, the composition of short-term liabilities (it might be bank debt, accounts payables to suppliers, taxes, etc.), previous net income, or even details on the EVA calculation.

To be able to obtain a first set of results considering the same possible decisions to those of Longinidis and Georgiadis (2011), we made the following assumptions regarding the missing information: i) balance sheet data before the planning horizon are incorporated in the optimization process; ii) tangible assets bought before the planning period were already depreciated; and iii) short term liabilities consist of accounts payables and taxes of previous profits, which we pay in year 1. We also had to calculate the real value for Cash, instead of considering it as a percentage of the net income.

Another point worth mentioning is that our model is deterministic in nature, while that of Longinidis and Georgiadis (2011) considers uncertainty through scenarios incorporation. However, note that to handle the scenarios, the authors create copies of the production variables, inventory variables, and flow variables, which are then used in independent copies of the constraints using such variables and in the objective function, which considers the weighted average of the net sales calculated using the aforementioned variables. Moreover, the possibility that different scenarios may lead to different network structures is not considered. In addition, the authors use constant values across scenarios for all variables, except for demand.

Therefore, the first experiment conducted consists of solving the problem originally proposed by Longinidis and Georgiadis (2011), considering the same decision making assumptions and objective function, and with the considerations referred to earlier.

The model for the problem instance described was solved optimally in 1.16 CPU seconds with 0% integrality gap. The total value created amounts to 7,929,450 monetary units.

It is important to note that the EVA maximization tends to create high levels of inventory, since inventory is considered an asset, which increases the value of the company. Consequently, in order to increase inventory, the company produces more quantities than those demanded by customers. Of course, the quantities produced are not equal to maximum capacity, since we have established limits for the company financial ratios.

Figure 6 depicts the network corresponding to the decisions determined by the base-case. It consists of the three already existent plants (P1, P2, and P3), three warehouses (W1, W2, and W3), and three distribution centers (DC1, DC2, and DC3).

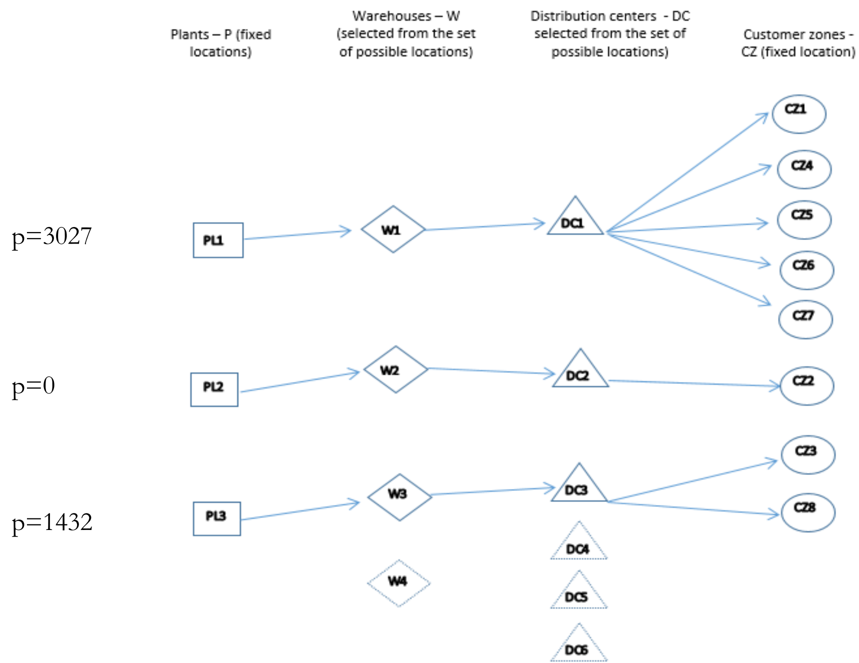

Figure 6 Network structure and total production quantities and product flows over the 4 years for the EVA base-case.

As we can see, the base-case creates the flows based on the low transportation costs among certain facilities, as already explained (see Table 7 to 9). As PL1 has the higher production capacity and initial inventory, and as the transportation costs among PL1, W1, and DC1 are smaller, the model determines the flows between those facilities to be the maximum quantities. Note that, the quantities produced by PL1 and PL3 refer to those products demanded by customers that are not available in the initial inventory. PL2 never produces during the completely planning horizon and it merely transfers inventory to W2. The products not required by customers remain in inventory.

	W1	**W2**	**W3**	W4
PL1	7467			
PL2		1516		
PL3			3174	

Table 7 Total aggregated flows transported from the plants to the warehouses for the EVA base-case.

	DC1	DC2	DC3	DC4	DC5	DC6
W1	7467					
W2		1516				
W3			3174			
W4						

Table 8 Total aggregated flows transported from the warehouses to the distribution centers for the EVA base -case.

	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
DC1	1351			2018	1239	1416	1443	
DC2		1516						
DC3			1630					1544
DC4								
DC5								
DC6								

Table 9 Total aggregated flows transported from the distribution centers to the customer zones for the EVA base-case.

Our solution of this base-case is used as comparison for all other computational experiments reported. This way, the advantages of our approach can be clearly shown.

5.2.2 Eva dynamic – opening

A dynamic environment allows for decision making at every period of the planning horizon, dealing with the dynamic characteristics of the supply chain system, consequence of demand fluctuations, lead-time delays, sales forecasting, amongst others. In addition, by doing so we can, up to a certain degree, account for uncertainty, since the network can be adapted to new realities, regardless of the source of the change. The advantage of considering a dynamic infrastructure is shown by solving the problem while allowing for opening facilities when necessary rather than only at the first time period.

However, in this particular case study, the structure of the model and the EVA created remain the same as in the base-case, where all the opening decisions are made in the first time period. This can be explained by the much lower transportation costs in some routes. Given the existing limits of the amount that can be transported, and to fully take advantage of them since the first year, the routes need to be used. This advantage can be clearly shown with a simple numerical example for year 1. Suppose that W2 was not opened in year 1. Although PL2 does not produce in year 1, it sends part of its inventory away to be sold, which are 1516 units in year 1. Considering the available warehouses, the cheapest alternative route would be PL2 sending to W1. However, as it can be seen from Table 10, sending these units through the alternative route in year 1 costs 86,757.75 monetary units more. As the cost of establishing W2 is 20,000 monetary units, it is more advantageous to open W2 in year 1 and benefit from the low transportations costs. The same happens with the other warehouses and distribution centers.

	Products	
	P1 to P6	**P7**
Quantities transferred from PL2 in year 1	1393	123
Route PL2 ->W2		
Unitary transportation cost	6.23	6.84
Total transportation cost for the route	8,678.39	841.32
Route PL2->W1		
Unitary transportation cost	63.11	68.01
Total transportation cost	87,912.23	8,365.23

Table 10 Transportation costs for alternative routes in year 1.

Of course that, if we increase a lot the cost of establishing warehouse 2 in year 1 and keep the cost of establishing W2 in year 2, the model would choose to open W2 only in year 2.

5.2.3 EVA dynamic – opening and closing

In this step, we introduced the possibility of also closing facilities. In our model, for a closure of a facility to occur, and consequently its sale, three conditions must be met: i) there must be a financial gain directly related to the sale; ii) with the closure of the facility, it is necessary to continue to ensure compliance with all constraints, in particular with demand; and iii) closing and selling the facility has to increase the corporate value of the company. To test the possibility of closing facilities we introduced a selling price for each facility and each time period of twice the facility establishment cost, which allowed to have a profit directly related with the sale (see Table 11), and no closing costs were considered.

	Year 1	Year 2	Year 3	Year 4
PL1, W1, DC1	80,000	80,000	80,000	80,000
PL2, W2, DC2	40,000	40,000	40,000	40,000
PL3, W3, DC3, DC6	32,000	32,000	32,000	32,000
W4, DC4	48,000	48,000	48,000	48,000
DC5	52,000	52,000	52,000	52,000

Table 11 Selling price for each facility at each time period (in monetary units).

In this situation, the total value created amounts to 8,231,900 monetary units, which is 3.81% larger than the value generated with the base-case, because closing and selling the facilities represents an income, which explains the increase in the EVA. The network created consists of the three already existent plants (P1, P2, and P3), the four potential warehouses (W1, W2, W3, and W4) and the six potential distribution centers (DC1, DC2, DC3, DC4, DC5, and DC6), that are opened in year 1. In year 2, PL2 is closed and, in year 4, the two other plants (PL1 and PL3) are also closed. W1, W2, W3, W4, DC2, DC3, DC4, DC5, and DC6 are closed and sold in year 4. Note that, as the closing decisions are made at the beginning of the time period, there must be at least one distribution center operating (in this case, DC1) to supply the customer zones. Although W4, DC4, DC5, and DC6 are opened in year 1, they do not operate. The opening decision of these facilities is a "real estate" one, meaning that the sale purpose of opening them is closing them in year 4 with a profit.

As in the base-case, PL2 does not produce any quantity, but transfers inventory to W1 and W2 in year 1, then in year 2 is closed. Regarding the other flows from plants to warehouses and from warehouses to distribution centers, and regardless of the quantities transported, they remain the same as in the base-case in the first three years. In year 4, the flows from distribution centers to customer zones are different because only DC1 is operating, thus suppling all the customer zones.

The closing decisions of the facilities at the end of the planning horizon allow producing and transferring in the first three years all the quantities needed to satisfy demand of the whole planning horizon and having a profit with the sale of the facilities when they are no longer needed. Note that, this is not a problem with the model, since selling the facilities improves the EVA. In addition, this is also not a problem for the company, since unless it is being closed down, in which case selling is the appropriate decision, before the end of the planning horizon (perhaps even after year 1) the model may be run again, with new and more accurate data, to determine the future decisions. Following this accounts to follow a receding (or rolling) horizon strategy. Such a strategy involves running the model for a large, in this case four years, planning horizon but using the model decisions only for part of the horizon, say one or two years. Then, new and more accurate data is gathered and the model is run again, either for the remaining time of the planning horizon, or a horizon with the same length, depending on the problem being solved. Henceforth, a solution of closing facilities at the end of the planning horizon, although seeming irrational, is not an issue.

5.2.4 EVA dynamic - opening and closing with financial aspects (full model)

In a final experiment, we gradually introduce some financial aspects in the model, which include the obligation of repayments to the bank, the adoption of an accounts payables policy, and the possibility of new capital entries from shareholders. These new aspects allow the model to become more realistic, bringing about some benefits, as shown during this experiment.

In a first step, we only introduced the obligation of repayments to the bank. The value created is 8,391,680 monetary units, which is 5.83% larger than the value created in the base-case, and 1.94% larger than the model without this obligation. The repayments to the bank reduce the company debt, which increases EVA. The network structure and flows established are the same as the ones established with the model without the obligation of repayments. In a second step, along with the obligation of debt repayments, we also consider an accounts payables policy in which 40% of the payments to the suppliers are made in credit and 60% in cash. Despite being a more realistic approach, the policy does not influence the results and the value generated is the same. This happens because with EVA as objective function, it is the amount of cost of sales that influences the value creation, regardless of being payed in cash or in credit. In a final step, we added the possibility of new capital entries. Although the original mathematical model from Longinidis and Georgiadis (2011) allows the possibility of capital entries, as a parameter, the case study used to test the model maintains the capital constant during the planning horizon. In our model, new capital entries are a variable, which is optimized by the model. To test this possibility, we have assumed upper limits for new capital entries of 50.000 monetary units in each year. However, because of the high value that the company has in cash before the planning horizon there is no need to obtain loans or capital entries from shareholders (which would reduce the EVA), and the value created remains the same, along with the network structure. Thus, the optimal network structure for the final experiment consists of the three existent plants (P1, P2 and P3), four warehouses (W1, W2, W3, and W4) and six distribution centers (DC1, DC2, DC3, DC4, DC5, and DC6) that are opened in the first year of the planning horizon. In year 2, PL2 is closed. In year 4, PL1, PL3, and all the warehouses and distribution centers except DC1 are closed. Recall the need of having at least on one distribution center operating, as previously explained. W4, DC4, DC5, and DC6 are opened in year 1, but are not used, as already explained.

Regarding the flows between facilities (see figures 7 to 10) and in addition to the differences in the flows values, there are also changes in the flow routes, mainly due to the closing of the facilities. In year 1, PL1, PL2, and PL3 supply W1, W2, and W3, respectively and PL2 also supplies W1; W1, W2, and W3 supply DC1, DC2, and DC3, respectively. DC1 supplies five of the eight customer zones (CZ1, CZ4, CZ5, CZ6, and CZ7), DC2 supplies CZ2, and DC3 supplies CZ3 and CZ8. In year 2, the only change in the network is that PL2 is closed and W2 is open but not operating. In year 3, the changes are in DC3 flows, which now supplies CZ3, CZ4 and CZ8. In year 4, the only existent flows are from DC1 to all the customer zones. All the other facilities are closed.

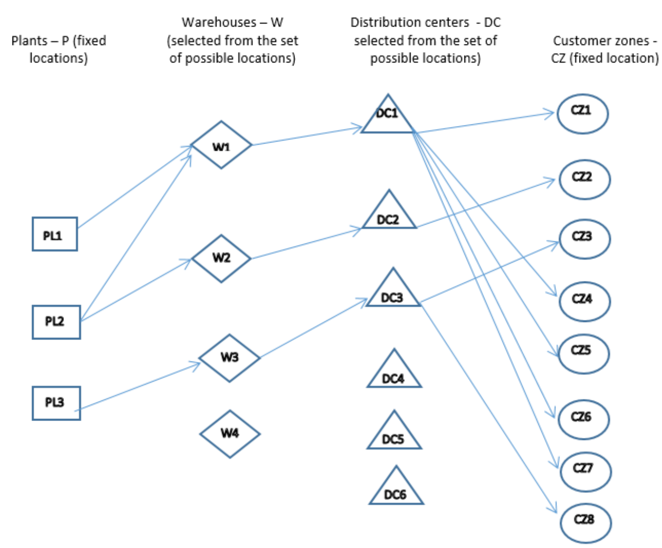

Figure 7 Network structure and used product flows in year 1 for EVA full-model.

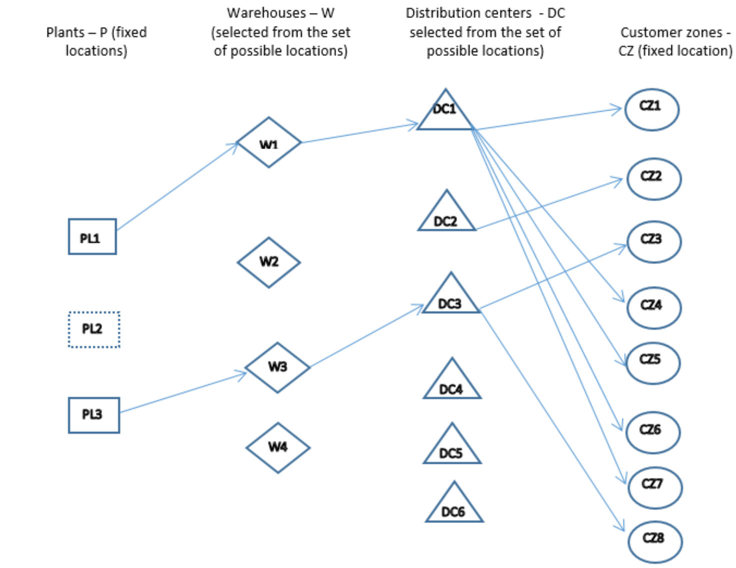

Figure 8 Network structure and used product flows in year 2 for EVA full-model.

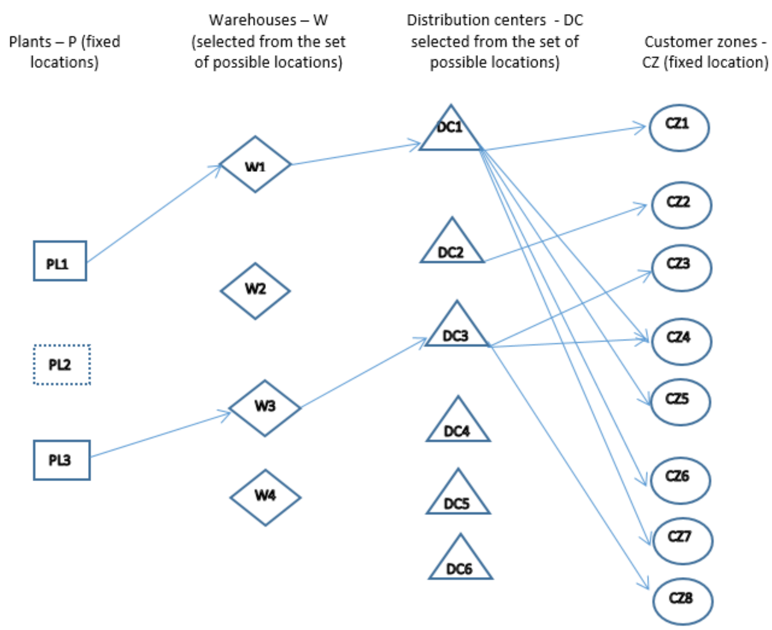

Figure 9 Network structure and used product flows in year 3 for EVA full-model.

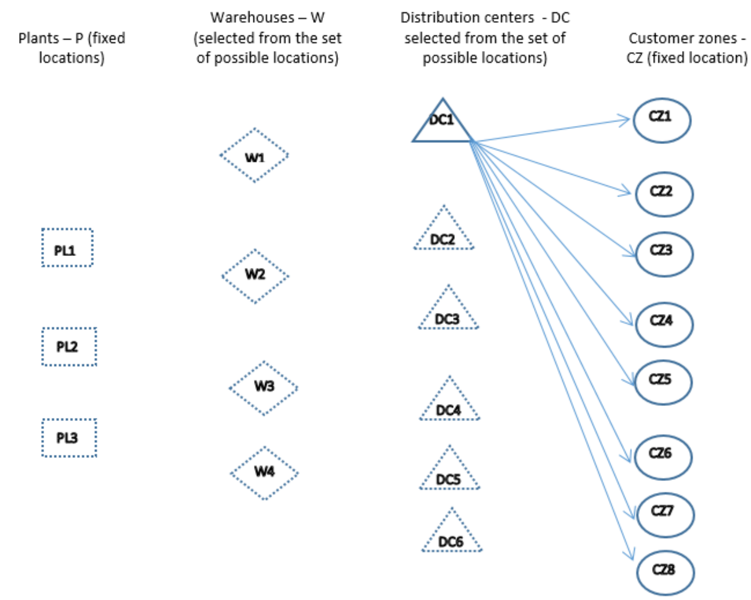

Figure 10 Network structure and used product flows in year 4 for EVA full-model.

Tables 12 to 14 provide the transportation flows between facilities and between facilities and customer zones for the full-model and for the base-case. These flows are the total quantities of products transported regardless of the product type over the 4-years planning horizon.

	W1	**W2**	**W3**	**W4**
PL1	7467			
PL2		1516		
PL3			3174	

a) obtained by the EVA base-case.

	W1	**W2**	**W3**	**W4**
PL1	8449			
PL2	100	1134		
PL3			2474	

b) obtained by the EVA full-model.

Table 12 Total aggregated flows transported from the plants to the warehouses for EVA full-model.

	DC1	**DC2**	**DC3**	**DC4**	**DC5**	**DC6**
W1	7467					
W2		1516				
W3			3174			
W4						

a) obtained by the EVA base-case.

	DC1	**DC2**	**DC3**	**DC4**	**DC5**	**DC6**
W1	8549					
W2		1134				
W3			2474			
W4						

b) obtained by the EVA full-model.

Table 13 Total aggregated flows transported from the warehouses to the distribution centers for EVA full-model.

	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
DC1	1351			2018	1239	1416	1443	
DC2		1516						
DC3			1630					1544
DC4								
DC5								
DC6								

a) obtained by the EVA base-case

	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
DC1	1351	382	414	1918	1239	1416	1443	386
DC2		1134						
DC3			1216	100				1158
DC4								
DC5								
DC6								

b) obtained by the EVA full-model.

Table 14 Total aggregated flows transported from the distribution centers to the customer zones for EVA full-model.

Regarding production, quantities (see Table 15), in year 1, the total production was 88 units, while in years 2 and 3 the total annual production increased to 1002 and 3053 units, respectively.

Year	PL1	PL2	PL3	Total
1	88	0	0	88
2	694	0	308	1 002
3	2 527	0	526	3 053
4	0	0	0	0
Total	**3 309**	**0**	**834**	**4 143**

Table 15 Production quantities by plant and time period for EVA full-model.

It is important to note that, since plants transfer to the warehouses only the quantities demanded by the customers, the final inventory of 8929 units remains at the plants.

5.3 Modelling with SVA as the objective function

The second set of experiments also aims to show the advantage of incorporating additional decisions, as well as calculating financial figures more accurately. However, it uses the Shareholder Value Analysis (SVA) as objective function. According to the theory already explained in Chapter 2, SVA is the most accepted line of thought to measure the value of a company.

SVA computes shareholder value (or equity value) by deducting the value of the long term liabilities at the end of the lifetime of the project from the value of the firm for the time period in analysis, which is obtained through de discounted free cash flow (DFCF) method. We used a growth rate in perpetuity of 0.5% to calculate the terminal value of the company.

Again, we tested the model by steps, in order to show the value created by the model improvements considered.

5.3.1 SVA base-case

As done in the EVA case (see Section 5.2.1), we consider a base-case, which only allows for opening facilities in the beginning of the planning horizon. Similarly, the base-case will be used to compare the improvements obtained by the extended version of the model.

The base-case was solved optimally in 32.28 CPU seconds with 0% integrality gap. Note that the solving time is much larger than that of EVA base-case, since the SVA calculation is more complex. The shareholder value created is 89,289,000 monetary units.

The network structure consists of the three already existent plants (PL1, PL2, and PL3), three warehouses (W1, W2, and W3) and five distribution centers (DC1, DC2, DC3, DC5, and DC6) that are opened at the beginning of the first year. The need to reduce inventory is clearly shown in the results: the small production quantities and the large flows lead to the opening of more distribution centers, in order to quickly reduce the high product quantities in stock.

Production quantities for the whole planning horizon in total amount only to 1398 units: PL1 produces 795 units, PL3 produces 602 units and PL2 does not produce at all. Note that the quantity produced is smaller than the one found in the EVA base-case, since SVA tends to reduce the quantities in inventory, in order to reduce the needs for working capital. A large number of flows is created between warehouses and distribution centers and between distribution centers and customer zones, as we can see in Figure 11.

Comparing the flows with those obtained in the EVA base-case, the total quantities transported from plants to warehouses are higher. PL2 transfers a much higher quantity, and PL1 slightly increases the transferred quantity (see Table 16). As W2 receives a much larger quantity, which is now used to supply more than one distribution center; more specifically it serves DC2, DC5, and DC6. Similarly, W1 receives more products, supplying DC1 and DC6 (see Table 17).

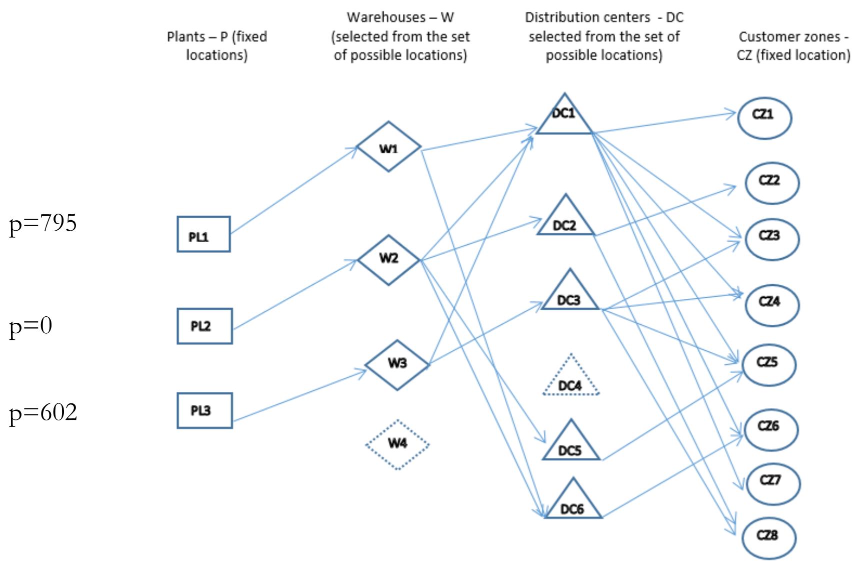

Figure 11 Network structure and used product flows for SVA base-case.

Since inventory was stored in five distribution centers, the quantity of flows between distribution centers and customer zones is much larger than the quantities of flows generated when EVA was the objective function (see Table 18). Note that most of the inventory is transferred from plants to warehouses and then to DC6, since the inventory cost at DC6 has the lower marginal inventory cost of all the facilities (at least 20% lower). DC6 receives 5818 units, supplies CZ6 with 512 units and stays with 5306 units in inventory. Only 878 units of inventory remain at the plants.

	W1	**W2**	**W3**	W4
PL1	7888			
PL2		6120		
PL3			3455	

a) obtained with SVA base-case.

	W1	**W2**	**W3**	W4
PL1	7468			
PL2		1516		
PL3			3175	

b) obtained with EVA base-case.

Table 16 Total aggregated flows transported from the plants to the warehouses for SVA base-case.

	DC1	**DC2**	**DC3**	DC4	**DC5**	**DC6**
W1	5350					2538
W2	100	2244			496	3280
W3	157		3298			
W4						

a) obtained with SVA base-case.

	DC1	**DC2**	**DC3**	DC4	DC5	DC6
W1	7468					
W2		1516				
W3			3175			
W4						

b) obtained with EVA base-case.

Table 17 Total aggregated flows transported from the warehouses to the distribution centers for SVA base-case.

	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
DC1	1351		114	1672	123	904	1443	
DC2		1516						728
DC3			1516	346	620			816
DC4								
DC5					496			
DC6						512		

a) obtained with SVA base-case.

	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
DC1	1351			2018	1239	1416	1443	
DC2		1516						
DC3			1630					1544
DC4								
DC5								
DC6								

b) obtained with EVA base-case.

Table 18 Total aggregated flows transported from the distribution centers to the customer zones for SVA base-case.

5.3.2 SVA dynamic – opening

In a second step, our model allows the company to make decisions in a dynamic environment. However, in this particular case study, all the opening decisions are made in the first time period, and the network structure is the same as in the base-case, similarly to what happened using EVA as the objective function.

5.3.3 SVA dynamic – opening and closing

Afterwards, we introduced in the base-case the possibility of opening and closing facilities at any time period of the planning horizon. To test this possibility we established favourable selling prices (twice the establishment price of each facility) and no closing costs. The shareholder value created is 89,488,900 monetary units, 0.22% larger than the value created in the base-case, because of the gains resulting from selling the plants. The network established consists of the three existent plants (PL1, PL2, and PL3), the four possible warehouses (W1, W2, W2 and W4) and the six possible distribution centers (DC1, DC2, DC3, DC4, DC5 and DC6). Closing decisions of the three plants are taken: PL1 and PL2 are closed in year 2 and PL3 is closed in year 4 (recall that all decisions of opening and closing occur at the beginning of the year). W1, W2, W3, and W4 are closed in year 4, as well as DC4.

Although PL2 does not produce any quantity, it transfers to W2 and W3 the products it has in stock, and PL1 produces and supplies its products to W1 and W4 in year 1. PL3 supplies W3 from year 1 to year 3 and is closed in year 4.

Warehouses supply the distribution centers in years 1, 2, and 3 and then are closed in year 4. W4 operates only in years 1 and 2 suppling DC4 and in year 3 is inactive, being closed and sold only in year 4. Although the selling price is the same during the four years, the sale occurs only in year 4 because the cash inflow is larger than the cash inflow generated if the sale is made in year 3. For a better understanding, see the example of the free cash flow to firm (FCFF) calculation for the sale of W4, illustrated in Table 19 (recall the relevant formulas for the discounted free cash flow calculation (DFCF), given in equations (2), (3), and (8) in Section 4.1). The acquisition cost of W4 in year 1 is equal to 26,000 monetary units and the selling price is equal to 52,000 monetary units, regardless of the year, and depreciation rate is 25% per year. However, the DFCF is 1,982.25 monetary units larger (7.9%) if the sale is made in year 4 rather than in year 3. This is explained by the increase in the accumulated depreciations, which decrease the net value of the assets and make the non-operating profit larger in year 4.

	Notation	Financial account	Year 1	Year 3	Year 4
		Non operating income		36,000.00	42,000.00
(A)	NOI	(+) sales price		48,000.00	48,000.00
		(-) net value (FAI-cumulated DPR)		12,000.00	6,000.00
(B)	DPR	Depreciation	6,000.00		
(C)	TR	Taxe rate	0.20	0.25	0.275
(D)	FAI	Fixed assets investment	2,4000.00		
(E)	DPR	Depreciation	6,000.00		
(F)	FCFF	Free cash flow to firm	-22,800.00	27,000.00	30,450.00
	r	Discount rate	0.015	0.025	0.03
	DFCF	Discounted free cash flow	-22,463.05	25,072.18	27,054.43

(F) = [(A) - (B)] x [1 - (C)] - [(D) - (E)]

Table 19 Discounted free cash flow calculation considering the sale of W4 in years 3 and 4 for SVA dynamic – opening and closing.

Regarding distribution centers, DC4 is closed in year 4, after serving CZ4 from year 1 to year 3. In year 4, the supply of CZ4 is made by DC1.

5.3.4 SVA dynamic - opening and closing with financial aspects (full model)

In a final step, we introduced in the previous version of the model the obligation of bank loans repayments, an accounts payables policy, and the possibility of new capital entries, which makes the model more adjusted to reality. To better understand the impact of these aspects we introduced one at the time.

The shareholder value created with the obligation of bank repayments is 90,332,700 monetary units, 0.94% larger than the one of the full dynamic version and 1.17% larger than the one of the SVA base-case. The network structure remains the same. As we are making bank repayments every year (450,000, 225,000, 112,500, and 56,250 monetary units in year 1, 2, 3, and 4, respectively), long term debt decreases and a smaller value is deducted from the free cash flow generated over the planning horizon, creating more value for the shareholders.

Next, we also consider an accounts payable policy. We assumed that 40% of the payments to suppliers are made in credit and 60% are made in cash. In this situation, the shareholder value created is 90,115,200 monetary units, 0.24% smaller. Due to the larger working capital needs (now, the working capital, which is the amount of money needed to support operating expenses, also contemplates the money needed to pay to suppliers) the free cash flow decreases, making the value created 217,500 monetary units lower. The network changes since now all the plants are closed in year 3, and DC4 and DC6 are closed in year 4. The closing of PL1 and PL2 is delayed one year, dividing the quantities transported throughout the years, thus reducing transportation costs per year in order to accomplish with cash financial ratios for each year.

Finally, we also introduced the possibility of new capital entries from shareholders. To test this functionality we have established a per year limit of 50,000 monetary units for the new capital entries, which represents the maximum that shareholders are willing to invest in the company, in order to receive a financial retribution in the future (through dividends distribution). With this new possibility, the model is complete. The model for the problem instance described was solved optimally in 172.81 CPU seconds with 0% integrality gap (once again, the complexity of the calculation increases). The company captures the maximum value of capital entries from shareholders from year 1 to year 4 and the shareholder value created increases to 90,115,800 monetary units, which is 0.93% larger than the value found in the base-case. Now the company has more money to make better operational decisions.

The structure of the network consists of the three existent plants, the four warehouses and the six distribution centers that are opened in the first year. PL2 closes in year 2, and PL1 and PL3 close in year 3. All the warehouses are closed in year 4 despite operating only in years 1 and 2, for the reasons already explained in the previous section (as the accumulated depreciation increases, the net value of the asset decreases, leading to a larger facilities sale profit). DC4 and DC6 are also closed in year 4. Although DC5 and DC6 start operating only in year 2, they are opened in year 1 for the same reasons: in the year of the sale, their net value is smaller.

Figures 12 to 15 illustrate the network structure during the planning horizon and tables 16 to 21 show the quantities produced, the quantities transported and the final inventories in each facility. The flows between facilities change, as well as the quantities transported. As it can be seen, in the first year PL1, PL2, and PL3 supply W1, W2, and W3, respectively; PL1 and PL2 also supply W4. In year 2, PL2 is closed and PL1 and PL3 maintain the existing flows.

In terms of flows between warehouses and distribution centers, they only exist in year 1 and 2 and W1, W2, W3, and W4 supply DC1, DC2, DC3, and DC4, respectively. In year 2, a larger number of flows is created: W1 supplies also DC4 and DC5; W2 supplies also DC4 and DC6; and W3 supplies also DC1, DC4 and DC5. In year 3, the warehouses are still open but not operating. In year 4, all the warehouses are closed and sold.

Existing flows between distribution centers and customer zones also change during the planning horizon. In year 1, DC1 supplies five customer zones (CZ1, CZ4, CZ5, CZ6, and CZ7); DC2 supplies CZ2; DC3 supplies three customer zones (CZ3, CZ4, and CZ8); DC4 supplies CZ4 and CZ8; and DC5 and DC6 do not operate in year 1. In year 2, DC1 supplies also CZ3; DC2 supplies also CZ8; DC3 supplies also CZ5; DC4 supplies CZ8 (and no longer CZ4); and DC5 and DC6 do not supply any customer zone, meaning that they are only accumulating inventory to deliver in the subsequent years. In year 3, DC1 reduces the quantity of existing flows, suppling only CZ1 and CZ7; DC2, DC3, DC5, and DC6 supply CZ2, CZ3, CZ5, and CZ6, respectively; DC4 supplies only CZ4 and CZ8. In year 4, DC4 and DC6 are closed; DC2 and DC5 remain with the same existing flows; DC1 supplies CZ1, CZ4, CZ6, and CZ7; and DC3 supplies CZ3 and CZ8.

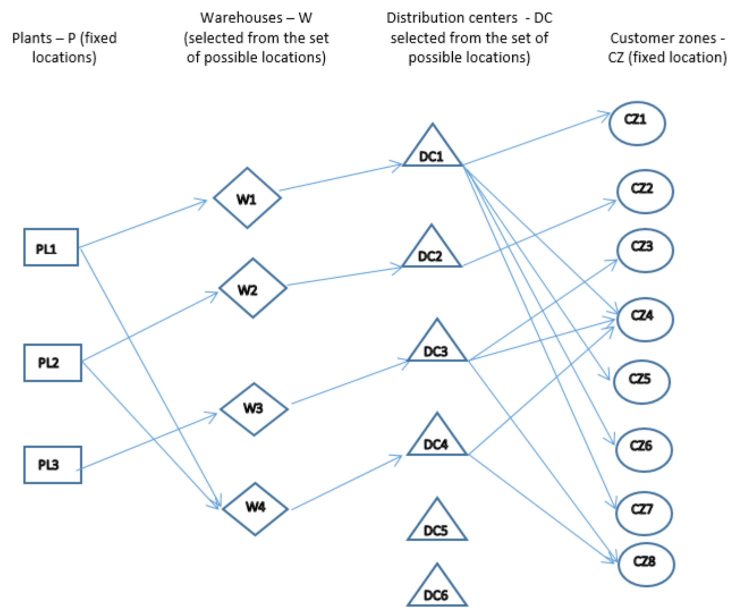

Figure 12 Network structure and used product flows for the complete model in year 1 for SVA full-model.

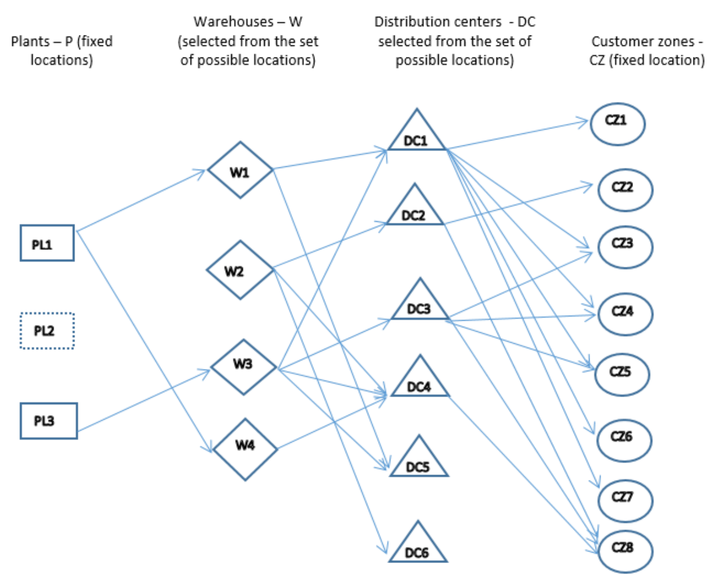

Figure 13 Network structure and used product flows for the complete model in year 2 for SVA full-model.

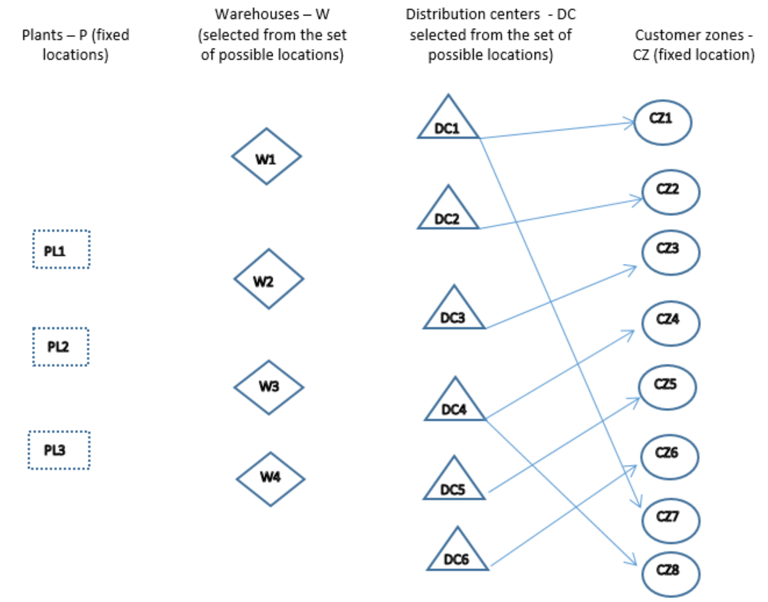

Figure 14 Network structure and used product flows for the complete model in year 3 for SVA full-model.

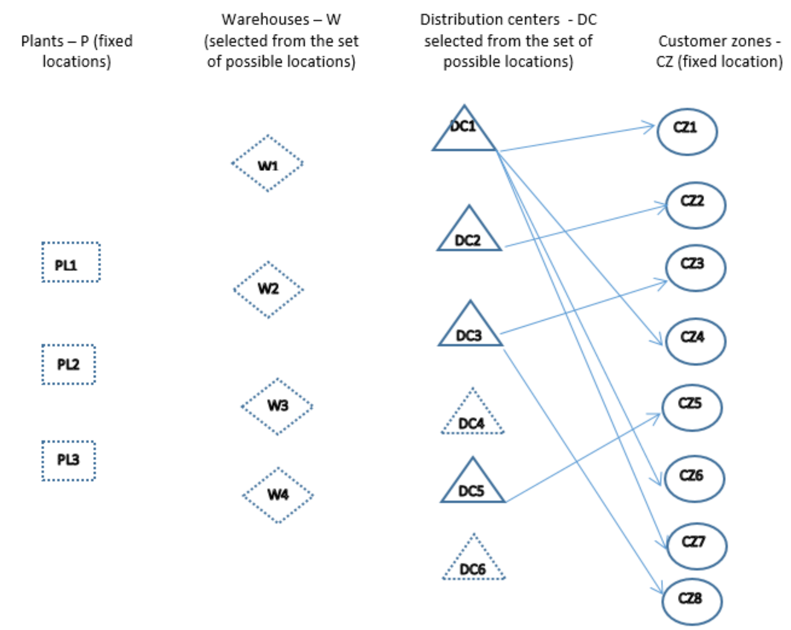

Figure 15 Network structure and used product flows for the complete model in year 4 for SVA full-model.

Production occurs only during the first two years of the planning horizon, and the total quantity produced is 1398 units (see Table 20). PL1 produces more than twice the quantity produced by PL3 and PL2 does not produce anything during the planning horizon. The total quantity produced is much smaller than the one produced when EVA was the objective function. With SVA as the objective function, the value of the company increases with low levels of production because payments to suppliers are smaller, thus the need for working capital is also smaller. However, with EVA as the objective function, producing more leads to higher inventories (which are a part of the current assets), hence improving the value of the company.

The final inventory for each plant and time period is shown in Table 17. PL2 closes at the beginning of year 2 with a final inventory of 3339 units, reducing its initial inventory in 83%; PL1, and PL3 are closed at the beginning of year 3, with a final inventory of 1968 and 878 units, which means an inventory reduction of 260% and 325%, respectively (see Table 21). Note that products that were not sold during the planning horizon are the ones that stay in final inventory (such as products 2, 4, and 7 in the case of PL1), and that the products that were produced in years 1 and 2 (such as products 3 and 6 in the case of PL1) have no final inventory.

Year	PL1	PL2	PL3	Total
1	0	0	16	16
2	966	0	416	1 382
3	0	0	0	0
4	0	0	0	0
Total	**966**	**0**	**432**	**1 398**

Table 20 Production quantities for each plant and time period for SVA full-model.

Year	PL1	PL2	PL3	Total
1	5181	3338	2927	11447
2	1968	3338	878	6185
3	1968	3338	878	6185
4	1968	3338	878	6185

Table 21 Final inventory quantities by plant and time period for SVA full-model.

The quantities of products transported from the plants to the warehouses (see Table 22) increase from year 1 to year 2, in accordance with the evolution of the number of used flows, as explained before. The quantity of products in inventory at the end of year 1 (see Table 23) is equal to the requirement for safety stock established in the case study. As the flows end in year 2, the final inventory is set to zero units.

Year 1	W1	W2	W3	W4	Total
PL1	1 698	0	0	214	1 912
PL2	0	2 472	0	311	2 783
PL3	0	0	818	0	818
Total	**1 698**	**2 472**	**818**	**525**	**5 513**
Year 2					
PL1	3 843	0	0	336	4 179
PL2	0	0	0	0	0
PL3	0	0	2 465	0	2 465
Total	**3 843**	**0**	**2 465**	**336**	**6 644**
Year 3					
Total	**0**	**0**	**0**	**0**	**0**
Year 4					
Total	**0**	**0**	**0**	**0**	**0**

Table 22 Aggregated flows transported from the plants to the warehouses for SVA full-model.

Year	W1	W2	W3	W4	Total
1	165	2076	104	14	2359
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0

Table 23 Inventory quantities by warehouse and time period for SVA full-model.

Regarding the flows between warehouses and distribution centers (see Table 24), the quantities transported are also in accordance with the movements in the previous echelons of the supply chain. Although the three warehouses have the same maximum handling capacity, it is W1 that handles with more quantities, which is justified by the lowest unit material handling and storage costs. All the flows satisfy the requirement of a minimum quantity being transported to each distribution center, which is equal to 100 units.

Year 1	DC1	DC2	DC3	DC4	DC5	DC6	Total
W1	1533	0	0	0	0	0	1533
W2	0	396	0	0	0	0	396
W3	0	0	714	0	0	0	714
W4	0	0	0	511	0	0	511
Total	**1533**	**396**	**714**	**511**	**0**	**0**	**3154**
Year 2							
W1	3796	0	0	100	112	0	4008
W2	0	1220	0	502	0	354	2076
W3	158	0	1789	115	507	0	2569
W4	0	0	0	350	0	0	350
Total	**3954**	**1220**	**1789**	**1067**	**619**	**354**	**9003**
Year 3							
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4							
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 24 Aggregated flows transported from the warehouses to the distribution centers for SVA full-model.

The final inventory at year 4 (see Table 25) is set to zero, because the planning horizon ends.

Year	DC1	DC2	DC3	DC4	DC5	DC6	Total
1	73	19	24	9	0	0	125
2	2263	760	1206	890	619	354	6092
3	1564	379	799	0	310	0	3052
4	0	0	0	0	0	0	0

Table 25 Final inventory quantities by distribution center and time period for SVA full-model.

Finally, the quantities transported from each distribution center to each customer zone (see Table 26) are in accordance with demand (see Appendix A). Appendix B shows the detailed results (by product) obtained with the model.

Year 1	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8	Total
DC1	337	0	0	99	310	354	360	0	1460
DC2	0	377	0	0	0	0	0	0	377
DC3	0	0	404	114	0	0	0	172	690
DC4	0	0	0	288	0	0	0	214	502
DC5	0	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0	0
Total	**337**	**377**	**404**	**501**	**310**	**354**	**360**	**386**	**3029**
Year 2									
DC1	338	0	114	388	210	354	360	0	1764
DC2	0	379	0	0	0	0	0	100	479
DC3	0	0	292	115	100	0	0	100	607
DC4	0	0	0	0	0	0	0	186	186
DC5	0	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0	0
Total	**338**	**379**	**406**	**503**	**310**	**354**	**360**	**386**	**3036**
Year 3									
DC1	338	0	0	0	0	0	361	0	699
DC2	0	381	0	0	0	0	0	0	381
DC3	0	0	407	0	0	0	0	0	407
DC4	0	0	0	504	0	0	0	386	890
DC5	0	0	0	0	309	0	0	0	309
DC6	0	0	0	0	0	354	0	0	354
Total	**338**	**381**	**407**	**504**	**309**	**354**	**361**	**386**	**3040**
Year 4									
DC1	338	0	0	510	0	354	362	0	1564
DC2	0	379	0	0	0	0	0	0	379
DC3	0	0	413	0	0	0	0	386	799
DC4	0	0	0	0	0	0	0	0	0
DC5	0	0	0	0	310	0	0	0	310
DC6	0	0	0	0	0	0	0	0	0
Total	**338**	**379**	**413**	**510**	**310**	**354**	**362**	**386**	**3052**
Aggregated demand	1351	1516	1630	2018	1239	1416	1443	1544	

Table 26 Aggregated flows transported from the distribution centers to the customer zones for SVA full-model.

The decisions described above resulted in the operating costs (production, transportation and inventory holding costs) presented in Table 23. Transportation costs represent the larger component of the operating costs (54.5%), followed by inventory holding costs (37.5%) and production costs (8%). We only have production costs in years 1 and 2, since there is no production in years 3 and 4, which happens due to the extremely high levels of inventory at the beginning of the planning horizon, as explained before. In years 3 and 4, there are no transportation costs from plants to warehouses and from warehouses to distribution centers, since plants are closed and the warehouses are not operating.

Inventory costs are decreasing over the planning horizon. The inventory costs at the plants in years 3 and 4 refer to the products that were already in inventory at the beginning of the planning horizon and that were not requested by the customers. Note that although the final inventory at the distribution centers is equal to zero (see Table 25) there is an inventory cost, since inventory is valued based on its average during the whole year.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Total**
Production costs	963	84,751	0	0	**85,714**
Transportation costs	152,717	303,856	59,518	66,295	**582,386**
PL->W	51,986	47,667	0	0	**99,653**
W->D	14,395	153,199	0	0	**167,594**
DC->CZ	86,336	102,990	59,518	66,295	**315,139**
Inventory costs	131,562	111,651	91,622	65,681	**400,516**
PL	120,941	75,089	52,634	52,634	**301,298**
W	10,092	10,092	0	0	**20,184**
DC	529	26,470	38,988	13,047	**79,034**

Table 27 Production, transportation, and inventory costs for each time period for SVA full-model.

Regarding financial decisions (see Table 28), the company does not need to resort to bank loans, since it has enough cash, as it can be seen from the initial balance sheet of the company. However, the company captures all the capital entries from shareholders. In addition, due to the high levels of inventory, production costs are very low, releasing money for investment. Therefore, the company is in a favourable position to make repayments to the bank, decreasing debt and maximizing the corporate shareholder value (SVA).

	Financial decisions				
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Total**
Investment	292,000	0	0	0	**194,000**
Loans	0	0	0	0	**0**
New capital entries	50,000	50,000	50,000	50,000	**200,000**
Repayments	450,000	225,000	112,500	56,250	**843,750**

Table 28 Investment and financial decisions for each time period for SVA full-model.

5.4 Discusssion of the results

In the previous sections, we described the two sets of experiments carried out in order to evaluate the impacts of i) the additional decisions allowed by incorporating the possibility of opening and closing facilities at any time period of the planning horizon and of ii) the proposed objective function, that maximizes corporate value of the company through the SVA method.

In the first set of experiments, we used the objective function proposed by Longinidis and Georgiadis (2011). We had to establish the base-case to make the comparisons, since that of Longinidis and Georgiadis (2011) could not be directly used to do so. In addition to some inconsistencies and discrepancies, some data is missing. In order to overcome these inconsistencies we had to make assumptions related with the financial situation of the company before the planning horizon and with the methodology adopted to calculate the EVA.

We reached a corporate value of 7,929,450 monetary units, which is substantially larger than the one reached by Longinidis and Georgiadis. This difference can be explained by the accounting treatment that we have assumed for the financial figures before the planning horizon, namely depreciations and short-term liabilities.

After establishing the base-case, we have extended the model to operate in a dynamic environment, allowing for opening facilities when necessary rather than only at the first time period. However, in this particular case study, it is more advantageous to start operating the warehouses and distribution centers in the first time period, in order to take advantage of the low transportation costs among certain facilities, as already explained.

Next, we incorporated the possibility of also closing facilities in the dynamic environment. We have established a selling price for each facility and no closing costs were considered, in order to have a financial advantage with the sale. Thus, the total value created is 3.81% larger than the value created with the base-case. The network changes, because all the warehouses and distribution centers are opened even if they are not needed, in order to have a profit with the sale. The three plants are closed: PL2 in year 2 and PL1 and PL3 in year 4. As already stated, if managers follow a rolling horizon strategy for decision-making, the closing of facilities at the end of the planning horizon is not an issue, since the model is to be periodically run. In a receding or rolling horizon strategy, the model is solved for a larger planning horizon with, say, n periods of time; however, from the decisions obtained only the ones of a smaller horizon, say, t<n, are implemented before solving the model again for either another n time periods or for the remaining n-t time periods, depending on the problem and solution strategy.

The final experiment, also considers several financial issues in the model in order to approach reality. These issues include the obligation of repayments to the bank, the adoption of an accounts payables policy and the possibility of new capital entries from shareholders. The EVA is 1.94% larger than the EVA obtained without financial aspects (just with opening and closing decisions in a dynamic environment) and 5.83% larger than the value created in the base-case. This larger value is mainly due to the repayments to the bank that reduce the company debt, which in turn increases EVA. Despite being a more realistic approach, the incorporation of an accounts payables policy did not change the results, because EVA is influenced by the amount of cost of sales but not by the payment term. New capital entries did not influence the results either, because the high value of cash of the company is enough to pay for all the expenses and investments, and there is no need to make loans or capital entries from shareholders (which would decrease the company value). The values obtained for the EVA and the structure of the network in each of the experiments are summarized in Table 29.

Characteristics	**EVA (monetary units)**	**Network structure**
Opening facilities in a static environment	7,929,450	PL1, PL2 and PL3 already existent; W1, W2 and W3 opened in year 1; DC1, DC2 and DC3 opened in year 1
Opening facilities in a dynamic environment	7,929,450	PL1, PL2 and PL3 already existent; W1, W2 and W3 opened in year 1; DC1, DC2 and DC3 opened in year 1;
Opening/closing facilities in a dynamic environment	8,231,900	PL1, PL2 and PL3 already existent; W1, W2, W3, and W4 opened in year 1; DC1, DC2, DC3, DC4, DC5, and DC6 opened in year 1; PL2 closed in year 2; PL1 and PL3 closed in year 4; W1, W2, W3, and W4 closed in year 4; DC2, DC3, DC4, DC5, and DC6 closed in year 4;
Opening/closing facilities in a dynamic environment, with re-payments, accounts payables and new capital entries	8,391,680	PL1, PL2 and PL3 already existent; W1, W2, W3, and W4 opened in year 1; DC1, DC2, DC3, DC4, DC5, and DC6 opened in year 1; PL2 closed in year 2; PL1 and PL3 closed in year 4; W1, W2, W3, and W4 closed in year 4; DC2, DC3, DC4, DC5, and DC6 closed in year 4;

Table 29 Value created and network structure obtained in each experiment, with EVA as the objective function.

In the second set of experiments, we used SVA as objective function. The experiments followed the same structure of the experiments made with EVA. In the first experiment, we had to establish the base-case to make the comparisons. We reached a corporate value of 89,289,000 monetary units. After establishing the base-case, we have extended the model to operate in a dynamic environment, allowing for opening facilities when necessary rather than only at the first time period. However, as with EVA as the objective function, in this particular case study all the warehouses and distribution centers are opened in the first time period, taking advantage of the low transportation costs among certain facilities since the beginning of the planning horizon. Then, we incorporated the possibility of closing any facility at any time period. After establishing prices in order to have a financial advantage with the sale, the three plants, the four warehouses and one distribution center are closed. The SVA obtained is 89,488,900 monetary units.

Lastly, the financial aspects were incorporated in the model: the obligation of repayments to the bank, the adoption of an accounts payables policy and the possibility of new capital entries from shareholders. The SVA obtained is 0.7% larger than the one obtained without financial aspects and 0.93% larger than that of the base-case. The network structure does not change, when comparing with the non-financial model. The increase in the company value is due to i) repayments to the bank which reduce debt, as was the case with EVA and to ii) the four years of new capital entries, which are a cash inflow that allows the company to make different and better operational options. The accounts payables policy reduces SVA (because working capital is larger), but this decrease is compensated by the increase obtained mainly with the repayments. Table 30 shows a summary of the results of the set of experiments with SVA as the objective function.

Characteristics	Shareholder value (monetary units)	Network structure
Opening facilities in a non-dynamic environment	89,289,700	PL1, PL2 and PL3 already existent W1, W2 and W3 opened in 1 DC1, DC2, DC3, DC5 and DC6 opened in year 1
Opening facilities in a dynamic environment	89,289,700	PL1, PL2 and PL3 already existent W1, W2 and W3 opened in 1 DC1, DC2, DC3, DC5 and DC6 opened in year 1
Opening and closing facilities in a dynamic environment	89,488,900	PL1, PL2 and PL3 already existent; W1, W2, W3, and W4 opened in year 1; DC1, DC2, DC3, DC4, DC5, and DC6 opened in year 1; PL2 closed in year 2; PL1 and PL3 closed in year 4; W1, W2, W3, and W4 closed in year 4; DC4 closed in year 4;
Opening and closing facilities in a dynamic environment, repayments, accounts payable policy and new capital entries	90,115,800	PL1, PL2 and PL3 already existent; W1, W2, W3, and W4 opened in year 1; DC1, DC2, DC3, DC4, DC5, and DC6 opened in year 1; PL2 closed in year 2; PL1 and PL3 closed in year 4; W1, W2, W3, and W4 closed in year 4; DC4 and DC6 closed in year 4;

Table 30 Value created and network structure obtained in each experiment, with SVA as the objective function.

After these experiments, we can conclude for the benefits of our extended model, irrespective of the objective function. On the one hand, the decisions obtained allow creating more value for the company and, on the other hand, it is a model with less assumptions and much closer to reality. The greatest value creation is due to both the operational factors, such as the decision making in a dynamic environment and the possibility of closing facilities, and the financial issues, mainly bank debt repayments.

However, even knowing that the benefits of our model do not depend on the objective function, we also propose a new objective function, that is, to maximize the model with SVA. SVA is one of the most accepted lines of thought on how corporate performance relates to shareholder value; instead of EVA, which is linked to conventional accounting approaches, as already discussed in the literature review. Recall that SVA is the present value of the cash flows of a company, plus its terminal value, which is an amount that represents the value of the company in perpetuity, discounted at the appropriate cost of capital. EVA deducts the cost of capital of a company from its net operating profit after taxes (the cost of capital is the amount of money used to fund a project multiplied by an average rate of return that a company expects to pay to its investors). However, the accounting character of EVA makes the model making some sort of irrational decisions, such as higher inventories in order to increase current assets value, obtaining a larger EVA, as already explained in the previous section.

To better show the advantage of using the full-model proposed in this thesis, we have calculated the value of each objective function using the optimal decisions obtained when optimizing the other objective function.

Tables 31 and 32 show these results for the base-case and for the extended version of the model. Table 31 reports the EVA value obtained by making the decisions that optimize it (optimum EVA) and also the EVA value corresponding to the decisions that optimize the SVA (calculated EVA). To obtain the latter value, we run the model while maximizing the SVA and then, using the optimal solution obtained, we calculate the corresponding EVA. Table 32 shows similar results but when optimizing the SVA.

By optimizing SVA the EVA is reduced by only 3.39% and 1.79% in the base-case and full-case, respectively; however, by optimizing EVA, the SVA, a more realistic measure of a company's performance, decreases 7.38% and 5.73%, respectively, proving the better performance of SVA as a corporate value measure. In addition, regardless of the objective function, the complete model is capable of improving the company's value: the optimum EVA increases by 5.83% and the optimum SVA increases 0.93%.

	Value created	
	Optimum EVA	**EVA calculated**
Using the simplest version of the model	7,929,450	*7,669,646*
Using the complete version of the model	8,391,680	*8,244,414*

Table 31 EVA value for both optimization criteria.

	Value created	
	Optimum SVA	**SVA calculated**
Using the simplest version of the model	89,289,000	*83,152,903*
Using the complete version of the model	90,115,800	*85,230,737*

Table 32 SVA value for both optimization criteria.

6 Conclusions and future work

A supply chain consists of a company or a set of companies directly involved in the upstream and downstream flows of products or services from a supplier to a customer in order to maximize competitiveness and profitability for the company and for the whole supply chain. Managing a supply chain is a complex task, mainly due to the large size of the physical network and its inherent uncertainties.

Many authors (Christopher and Ryals, 1999; Walters, 1999; Lambert and Burduroglu, 2000) argue that supply chain strategy and logistics decisions have a central position in shareholder value creation. Investment decisions on a new supply chain network are critical to the company's financial health, therefore should be considered as critical inputs to financial planning and supply chain decisions. Therefore, and corporate finances should also be accounted for when modelling supply chains.

However, literature on supply chain models that incorporate financial aspects is still scarce. While some studies consider financial aspects as known parameters used in constraints and in the objective function, other studies consider financial aspects as endogenous variables, but are too focused on scheduling and planning problems of batch process industries.

Lambert and Burduroglu (2000) present different methods to evaluate the value generated by logistics investments. Some of these methods are customer satisfaction, customer value-added, total cost analysis, segment profitability analysis, strategic profit model, and shareholder value. One of the most accepted lines of thought on how corporate performance relates to shareholder value is shareholder value analysis (SVA), introduced by Rappaport in 1986 (Mills and Print, 1995; Lambert and Burduroglu, 2000; and Klibi et al., 2010). To Rappaport (1986, *in* Lambert and Burduroglu, 2000) a business is worth the net present value of its cash flows discounted at the appropriate cost of capital.

Considering the scarcity of models that incorporate this thinking, we propose a mathematical model to address the problem of designing a supply chain network integrating strategical and tactical decisions with financial decisions and considerations. Our model determines number, locations, and sizes of the facilities (plants, warehouses, and distribution centers); production (product mix and produced quantities at each plant), inventory (which products and quantities are stocked at each facility), and distribution (product flows); and investment decisions (loans and bank repayments, as well as new capital entries from shareholders). This constitutes a contribution to literature, since the existing works consider the capital entries as a parameter.

Regarding the constrains, in addition to the usual operational constrains, we also consider minimum and/or maximum threshold values for performance ratios, efficiency ratios, liquidity ratios, and leverage ratios. The objective function of the model is the maximization of the shareholder value, through the SVA method, which is an innovation in the modelling of general purpose SCND.

The work proposed here extends that of Longinidis and Georgiadis (2011), since it uses a formulation in a dynamic environment that approaches reality, allowing to make opening and closing decisions for every time period, and not only opening decisions at the beginning of the planning horizon. It also allows establishing new plants, and not only warehouses and distribution centers. In addition, it considers accounting rules and uses less assumptions: considers decisions on repayments, improves depreciation and cash calculations, and allows for creating an accounts payable policy. Finally, the objective function had not yet been used in general SCND problems.

The applicability and benefits or our work were illustrated with the case study used by Longinidis and Georgiadis (2011), which was gently provided by the authors. We made two sets of experiments in order to evaluate the improvements that could be achieved by our model in relation to the original work of Longinidis and Georgiadis (2011).

In the first set of experiments, we used the same objective function of the original work, the EVA. However, we had to establish a base-case to make the comparisons, since that of Longinidis and Georgiadis (2011) cannot be directly used to do so. In addition to some inconsistencies and discrepancies, some data is missing, and we had to make some strong assumptions. After establishing the base-case, we have extended the model to operate in a dynamic environment, allowing for opening and closing facilities when necessary, rather than only at the first time period. The total value created with the improvements in the operational model is 3.81% larger than the value created with the base-case, due to the facilities sale gains. In the final EVA experiment, we have introduced some financial aspects in the model in order to model reality closer. These aspects include the obligation of repayments to the bank, the adoption of an accounts payables policy and the possibility of new capital entries from shareholders. The EVA is 1.94% larger than the EVA obtained without financial aspects and 5.83% larger than the value created in the base-case. This larger value is mainly due to the repayments to the bank that reduce the company debt, which in turn increases EVA. Part of this work, considering debt repayments and new capital entries as decision variables, improving on the calculation of some financial values, as well as introducing infrastructure dynamics while maximizing EVA, was already published as a book chapter (see Borges et al., 2019).

In the second set of tests, we used SVA as objective function. The experiments followed the same structure of the experiments made with EVA as the objective function. In the first experiment, we had to establish the base-case to make the comparisons. Then, we have extended the model to operate in a dynamic environment, allowing for opening/closing facilities when necessary, and the value created is 0,22% larger than the base-case. Lastly, the financial aspects were incorporated in the model: the obligation of repayments to the bank, the adoption of an accounts payables policy and the possibility of new capital entries from shareholders. The SVA obtained is 0.7% larger than the SVA obtained without financial aspects and 0.93% larger than the value created in the base-case.

In a direct comparison between EVA and SVA, we demonstrated that SVA is a better measure of the company corporate value, since the EVA obtained when optimizing with SVA is larger than the SVA obtained when optimizing with EVA. In addition, recall that, while EVA tends to increase inventories, since inventories are a company asset, thus increasing the EVA value, SVA tends to reduce inventories, in order to minimize the cash outflows, thus increasing SVA. Consequently, SVA is a more rational measure of the company value, which is in accordance with the literature review.

Moreover, after these experiments, we can conclude for the benefits of our extended model, irrespective of the objective function. On the one hand, the decisions obtained allow creating more value for the company and, on the other hand, it is a model with less assumptions and much closer to reality. The increase in the value created is both due to operational factors, such as the decision-making in a dynamic environment and the possibility of closing facilities, and to financial aspects, mainly bank debt repayments.

However, this work is limited in several ways; the most relevant limitation is that our model has only been tested on a single case study. It would be of great importance to test the model in other case studies, with a larger planning horizon and with more adherence to reality. Furthermore, we are assuming that every time that a facility is opened it is immediately operational, which does not happen in a real world situation. We also assume a network problem where facilities can only be supplied by the facilities in the previous echelon of the supply chain; however, real world situations often consider the possibility of direct sales, e.g., sales from producers to final customer, or to sales among similar facilities, e.g., from warehouse to warehouse.

Finally, we suggest some research directions to follow in the future. A first suggestion is to incorporate uncertainty into some parameters such as demand, costs, product prices and some financial parameters such as interest rate and growth rate in perpetuity, in order to obtain a model or solution approach closer to reality.

We can also add some operational decision variables, such as new facilities capacity, and to calculate the cost of capital inside the model, using the weighted average cost of capital methodology.

Another possibility is to incorporate the recent trends in supply chain network design. One of these trends is the green supply chain; leading to models with a closed-loop structure, addressing both forward and reverse flows. Another one is sustainability, which considers that economic, social, environmental, technological, and political aspects should be included in the supply chain design.

With these extensions (all or some) the model would become much more complex, which in turn would increase its computational complexity. Therefore, exploring other type of algorithms, such as metaheuristics, to solve the problem could be another direction for future work.

APPENDIX A

Longinidis and Georgiadis (2011) case study

Products (tons/year)	Plants		
	PL1	PL2	PL3
P1	158	0	972
P2	2268	1411	778
P3	1701	1058	607
P4	1512	1328	540
P5	0	996	0
P6	812	664	416
P7	642	664	416

Table 33 Maximum production capacity.

Plant	Resource	Product							Resource availability (h/year)
		P1	P2	P3	P4	P5	P6	P7	
PL1	E1	0.2381	0	0	0	0.7936	0	0	120
	E2	0	0.0463	0.0617	0.0694	0	0	0	105
	E3	0	0	0	0	0	0	0.1634	105
PL2	E1	0.2178	0	0.3742	0	0	0	0	105
	E2	0	0	0	0.0793	0.1054	0.1582	0.1582	105
	E3	0	0.074	0.1	0	0	0	0	105
PL3	E1	0	0	0.1976	0.2222	0	0	0	120
	E2	0	0	0	0	0.7789	0.3968	0.3968	165
	E3	0.1200	0.1543	0	0	0	0	0	120

Table 34 Coefficient of utilization of resources.

	Demand, year 1								
Product	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8	Total
P1	50	0	0	115	0	0	0	0	165
P2	0	53	105	0	0	0	155	0	313
P3	187	115	0	306	310	0	0	0	918
P4	0	103	115	0	0	0	205	192	615
P5	0	76	0	0	0	0	0	0	76
P6	100	0	95	0	0	354	0	194	743
P7	0	30	89	80	0	0	0	0	199
Total	337	377	404	501	310	354	360	386	3029

Table 35 Demand by product in time period 1.

Demand, year 2									
Product	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**	**Total**
P1	50	0	0	115	0	0	0	0	165
P2	0	53	105	0	0	0	155	0	313
P3	188	116	0	308	310	0	0	0	922
P4	0	104	116	0	0	0	205	192	617
P5	0	76	0	0	0	0	0	0	76
P6	100	0	96	0	0	354	0	194	744
P7	0	30	89	80	0	0	0	0	199
Total	338	379	406	503	310	354	360	386	3036

Table 36 Demand by product in time period 2.

Demand, year 3									
Product	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**	**Total**
P1	50	0	0	116	0	0	0	0	166
P2	0	54	106	0	0	0	156	0	316
P3	188	117	0	308	309	0	0	0	922
P4	0	103	116	0	0	0	205	192	616
P5	0	77	0	0	0	0	0	0	77
P6	100	0	95	0	0	354	0	194	743
P7	0	30	90	80	0	0	0	0	200
Total	338	381	407	504	309	354	361	386	3040

Table 37 Demand by product in time period 3.

Demand, year 4									
Product	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**	**Total**
P1	50	0	0	116	0	0	0	0	166
P2	0	53	106	0	0	0	156	0	315
P3	188	115	0	308	310	0	0	0	921
P4	0	103	115	0	0	0	206	192	616
P5	0	76	0	0	0	0	0	0	76
P6	100	0	95	0	0	354	0	194	743
P7	0	32	97	86	0	0	0	0	215
Total	338	379	413	510	310	354	362	386	3052

Table 38 Demand by product in time period 4.

Products	Production			Storage		
	PL1	PL2	PL3	PL1	PL2	PL3
P1-P6	61.27	59.45	61.44	8.25	8.55	8.98
P7	256.90	268.50	270.80	8.25	8.55	8.98

Table 39 Production and storage costs at plants in relative money units per ton.

Plant	Products	Wharehouse			
		W1	W2	W3	W4
PL1	P1-P6	5.49	63.11	67.28	31.09
	P7	5.6	68.01	72.49	33.28
PL2	P1-P6	65.07	6.23	75.94	48.86
	P7	86.95	6.84	101.46	64.65
PL3	P1-P6	80.41	83.76	6.5	59.76
	P7	99.15	103.24	6.78	73.25

Table 40 Transportation cost from plants to warehouses, in relative money units per ton.

Wharehouse	Infrastructure cost	Inventory Cost
W1	40,000	8.25
W2	20,000	8.55
W3	16,000	8.98
W4	24,000	8.93

Table 41 Warehouses infrastructure costs and inventory costs in relative money units per ton.

Wharehouse	Products	Distribution center					
		DC1	DC2	DC3	DC4	DC5	DC6
W1	P1-P6	4.25	78.95	81.11	30.89	74.06	33.31
	P7	4.25	79.83	82.01	31.19	74.87	33.66
W2	P1-P6	63.1	4.55	67.94	50.09	114.34	43.70
	P7	65.12	4.55	70.10	51.64	118.10	46.10
W3	P1-P6	77.08	80.69	4.98	54.59	99.20	103.22
	P7	95.00	99.43	4.98	66.81	122.42	127.66
W4	P1-P6	32.79	67.33	62.06	4.93	92.37	62.88
	P7	33.13	68.09	62.75	4.93	93.43	63.59

Table 42 Transportation cost from warehouses to distribution centers, in relative money units per ton.

Distribution center	Infrastructure cost	Inventory Cost
DC1	40,000	8.25
DC2	20,000	8.55
DC3	16,000	8.98
DC4	24,000	8.93
DC5	26,000	8.85
DC6	14,000	6.90

Table 43 Distribution centers infrastructure costs and inventory costs in relative money units per ton.

Distribution center	Product	Customer zone							
		CZ1	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**
DC1	P1-P6	0.00	75.61	54.51	12.30	70.34	29.89	17.58	119.57
	P7	0.00	73.12	52.71	11.90	68.02	28.9.	17.00	15.63
DC2	P1-P6	73.55	0.00	8.68	73.55	136.40	87.23	83.81	118.02
	P7	73.20	0.00	78.31	73.20	136.20	86.82	83.42	117.47
DC3	P1-P6	73.28	76.61	19.96	49.96	94.93	99.93	63.28	83.30
	P7	81.65	85.36	24.96	55.67	105.78	111.34	70.52	88.25
DC4	P1-P6	26.58	58.47	53.16	3.29	81.51	54.93	30.12	79.23
	P7	24.76	54.48	49.53	3.89	75.95	51.18	28.06	72.46
DC5	P1-P6	77.16	154.33	109.96	84.88	7.15	90.67	59.80	136.97
	P7	77.52	155.04	110.47	85.27	7.98	91.09	60.08	137.60
DC6	P1-P6	27.08	84.65	79.57	38.93	79.57	17.42	43.32	143.90
	P7	32.65	102.06	95.93	46.94	95.93	18.06	51.03	173.50

Table 44 Transportation cost from distribution centers to customer zones, in relative money units per ton.

	Price								
Product	**CZ1**	**CZ2**	**CZ3**	**CZ4**	**CZ5**	**CZ6**	**CZ7**	**CZ8**	**Total**
P1	250	0	0	230	0	0	0	0	480
P2	0	240	230	0	0	0	270	0	740
P3	0	270	0	230	250	0	0	0	750
P4	440	430	460	0	0	0	410	440	2180
P5	0	230	0	0	0	0	0	0	230
P6	420	0	430	0	0	400	0	430	1680
P7	0	610	600	600	0	0	0	0	1810
Total	1110	1780	1720	1060	250	400	680	870	7870

Table 45 Price of products for each customer zone, in relative money units per ton.

Account	Value
Assets	500,000
Tangible assets	500,000
Intangible assets	0,000
Current assets	1979,088
Cash	550,000
Receivable accounts	50,000
Inventory	1379,088
Total Assets	**2479,088**
Equity	1129,088
Common stock	1129,088
Retained earning	0,000
Debt	1350,000
Short term liabilities	450,000
Long term liabilities	900,000
Total Debt and Equity	**2479,088**

Table 46 Balance sheet at the beginning of the planning period, in relative money units per ton.

Financial parameter	Year 1	Year 2	Year 3	Year 4
Depretiation rate	0.250	0.250	0.250	0.250
Short term interest rate	0.035	0.040	0.045	0.050
Long term interest rate	0.070	0.075	0.080	0.085
Taxe rate	0.200	0.225	0.250	0.275
Cost of capital rate	0.015	0.020	0.025	0.030

Table 47 Financial cycle parameters in each time period.

Financial ratio	Bound
Current ratio	2.00
Quick ratio	1.25
Cash ratio	1.00
Fixed assets turnover ratio	1.10
Receivables turnover ratio	1.67
Total-debt ratio	0.60
Debt-equity ratio	1.50
Long term debt ratio	0.80
Cash coverage ratio	5.00
Profit margin ratio	0.05
Return on assets ratio	0.01
Return on equity ratio	0.02

Table 48 Bounds for financial ratios.

APPENDIX B

Detailed results of the complete model with SVA as the objective function

Year	PL1							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	0	0	0	0	0	0
2	0	0	315	0	0	651	0	966
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
Total	**0**	**0**	**315**	**0**	**0**	**651**	**0**	**966**

Table 49 Production quantities in PL1 by product and in each time period for SVA full-model.

Year	PL2							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 50 Production quantities in PL2 by product and in each time period for SVA full-model.

Year	PL3							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	0	0	0	16	0	16
2	0	0	0	0	0	416	0	416
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**432**	**0**	**432**

Table 51 Production quantities in PL3 by product and in each time period for SVA full-model.

	W1							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
PL1	58	180	605	248	0	513	93	1 698
PL2	0	0	0	0	0	0	0	0
PL3	0	0	0	0	0	0	0	0
Total	**58**	**180**	**605**	**248**		**513**	**93**	**1 698**
Year 2								
PL1	100	442	1 411	707	0	950	233	3 843
PL2	0	0	0	0	0	0	0	0
PL3	0	0	0	0	0	0	0	0
Total	**100**	**442**	**1 411**	**707**		**950**	**233**	**3 843**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 52 Flows transported from the plants to W1 by product and in each time period for SVA full-model.

	W2							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
PL1	0	0	0	0	0	0	0	0
PL2	0	214	769	420	305	642	123	2 472
PL3	0	0	0	0	0	0	0	0
Total	**0**	**214**	**769**	**420**	**305**	**642**	**123**	**2 472**
Year 2								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 53 Flows transported from the plants to W2 by product and in each time period for SVA full-model.

Year 1	W3							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
PL1	0	0	0	0	0	0	0	0
PL2	0	0	0	0	0	0	0	0
PL3	134	122	28	132	0	298	104	818
Total	**134**	**122**	**28**	**132**	**0**	**298**	**104**	**818**
Year 2								
PL1	0	0	0	0	0	0	0	0
PL2	0	0	0	0	0	0	0	0
PL3	369	300	578	407	0	549	261	2 465
Total	**369**	**300**	**578**	**407**	**0**	**549**	**261**	**2 465**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 54 Flows transported from the plants to W3 by product and in each time period for SVA full-model.

Year 1	W4							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
PL1	0	0	0	214	0	0	0	214
PL2	0	0	289	0	0	22	0	311
PL3	0	0	0	0	0	0	0	0
Total	**0**	**0**	**289**	**214**	**0**	**22**	**0**	**525**
Year 2								
PL1	0	0	0	336	0	0	0	336
PL2	0	0	0	0	0	0	0	0
PL3	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**336**	**0**	**0**	**0**	**336**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 55 Flows transported from the plants to W4 and in each time period for SVA full-model.

	DC1							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
W1	53	161	545	218	0	473	83	1 533
W2	0	0	0	0	0	0	0	0
W3	0	0	0	0	0	0	0	0
W4	0	0	0	0	0	0	0	0
Total	**53**	**161**	**545**	**218**	**0**	**473**	**83**	**1533**
Year 2								
W1	105	461	1 359	718	0	990	163	3 796
W2	0	0	0	0	0	0	0	0
W3	158	0	0	0	0	0	0	158
W4	0	0	0	0	0	0	0	0
Total	**263**	**461**	**1 359**	**718**	**0**	**990**	**163**	**3 954**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 56 Flows transported from the warehouses to DC1 by product and in each time period for SVA full-model.

	DC2							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
W1	0	0	0	0	0	0	0	0
W2	0	55	119	108	79	4	31	396
W3	0	0	0	0	0	0	0	0
W4	0	0	0	0	0	0	0	0
Total	**0**	**55**	**119**	**108**	**79**	**4**	**31**	**396**
Year 2								
W1	0	0	0	0	0	0	0	0
W2	0	159	342	312	226	90	91	1 220
W3	0	0	0	0	0	0	0	0
W4	0	0	0	0	0	0	0	0
Total	**0**	**159**	**342**	**312**	**226**	**90**	**91**	**1 220**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 57 Flows transported from the warehouses to DC2 by product and in each time period for SVA full-model.

	DC3							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
W1	0	0	0	0	0	0	0	0
W2	0	0	0	0	0	0	0	0
W3	118	109	4	115	0	275	93	714
W4	0	0	0	0	0	0	0	0
Total	**118**	**109**	**4**	**115**	**0**	**275**	**93**	**714**
Year 2								
W1	0	0	0	0	0	0	0	0
W2	0	0	0	0	0	0	0	0
W3	111	313	96	425	0	572	272	1 789
W4	0	0	0	0	0	0	0	0
Total	**111**	**313**	**96**	**425**	**0**	**572**	**272**	**1 789**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 58 Flows transported from the warehouses to DC3 by product and in each time period for SVA full-model.

	DC4							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
W1	0	0	0	0	0	0	0	0
W2	0	0	0	0	0	0	0	0
W3	0	0	0	0	0	0	0	0
W4	0	0	289	200	0	22	0	511
Total	**0**	**0**	**289**	**200**	**0**	**22**	**0**	**511**
Year 2								
W1	0	0	0	20	0	0	80	100
W2	0	0	308	0	0	194	0	502
W3	115	0	0	0	0	0	0	115
W4	0	0	0	350	0	0	0	350
Total	**115**	**0**	**308**	**370**	**0**	**194**	**80**	**1 067**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 59 Flows transported from the warehouses to DC4 by product and in each time period for SVA full-model.

	DC5							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 2								
W1	0	0	112	0	0	0	0	112
W2	0	0	0	0	0	0	0	0
W3	0	0	507	0	0	0	0	507
W4	0	0	0	0	0	0	0	0
Total	**0**	**0**	**619**	**0**	**0**	**0**	**0**	**619**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 60 Flows transported from the warehouses to DC5 by product and in each time period for SVA full-model.

	DC6							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 2								
W1	0	0	0	0	0	0	0	0
W2	0	0	0	0	0	354	0	354
W3	0	0	0	0	0	0	0	0
W4	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**354**	**0**	**354**
Year 3								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Year 4								
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 61 Flows transported from the warehouses to DC6 by product and in each time period for SVA full-model.

Year 1	CZ1							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	50	0	187	0	0	100	0	337
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**50**	**0**	**187**	**0**	**0**	**100**	**0**	**337**
Year 2								
DC1	50	0	188	0	0	100	0	338
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**50**	**0**	**188**	**0**	**0**	**100**	**0**	**338**
Year 3								
DC1	50	0	188	0	0	100	0	338
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**50**	**0**	**188**	**0**	**0**	**100**	**0**	**338**
Year 4								
DC1	50	0	188	0	0	101	0	338
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**50**	**0**	**188**	**0**	**0**	**101**	**0**	**338**

Table 62 Flows transported from the distribution centers to CZ1 by product and in each time period for SVA full-model.

	CZ2							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	0	0	0	0	0	0	0
DC2	0	53	115	103	76	0	30	377
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	0	53	115	103	76	0	30	377
Year 2								
DC1	0	0	0	0	0	0	0	0
DC2	0	53	116	104	76	0	30	379
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**53**	**116**	**104**	**76**	**0**	**30**	**379**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	54	117	103	77	0	30	381
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**54**	**117**	**103**	**77**	**0**	**30**	**381**
Year 4								
DC1	0	0	0	0	0	0	0	0
DC2	0	53	115	103	76	0	32	379
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**53**	**115**	**103**	**76**	**0**	**32**	**379**

Table 63 Flows transported from the distribution centers to CZ2 by product and in each time period for SVA full-model.

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	CZ3							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	105	0	115	0	95	89	404
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**105**	**0**	**115**	**0**	**95**	**89**	**404**
Year 2								
DC1	0	0	0	114	0	0	0	114
DC2	0	0	0	0	0	0	0	0
DC3	0	105	0	2	0	96	89	292
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**105**	**0**	**116**	**0**	**96**	**89**	**406**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	106	0	116	0	95	90	407
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**106**	**0**	**116**	**0**	**95**	**90**	**407**
Year 4								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	106	0	115	0	95	97	413
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**106**	**0**	**115**	**0**	**95**	**97**	**413**

Table 64 Flows transported from the distribution centers to CZ3 by product and in each time period for SVA full-model.

	CZ4							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	1	0	18	0	0	0	80	99
DC2	0	0	0	0	0	0	0	0
DC3	114	0	0	0	0	0	0	114
DC4	0	0	288	0	0	0	0	288
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**115**	**0**	**306**	**0**	**0**	**0**	**80**	**501**
Year 2								
DC1	0	0	308	0	0	0	80	388
DC2	0	0	0	0	0	0	0	0
DC3	115	0	0	0	0	0	0	115
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**115**	**0**	**308**	**0**	**0**	**0**	**80**	**503**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	116	0	308	0	0	0	80	504
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**116**	**0**	**308**	**0**	**0**	**0**	**80**	**504**
Year 4								
DC1	116	0	308	0	0	0	86	510
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**116**	**0**	**308**	**0**	**0**	**0**	**86**	**510**

Table 65 Flows transported from the distribution centers to CZ4 by product and in each time period for SVA full-model.

	CZ5							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	0	310	0	0	0	0	310
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**310**	**0**	**0**	**0**	**0**	**310**
Year 2								
DC1	0	0	210	0	0	0	0	210
DC2	0	0	0	0	0	0	0	0
DC3	0	0	100	0	0	0	0	100
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**310**	**0**	**0**	**0**	**0**	**310**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	309	0	0	0	0	309
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**309**	**0**	**0**	**0**	**0**	**309**
Year 4								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	310	0	0	0	0	310
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**310**	**0**	**0**	**0**	**0**	**310**

Table 66 Flows transported from the distribution centers to CZ5 by product and in each time period for SVA full-model.

	CZ6							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	0	0	0	0	354	0	354
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**354**	**0**	**354**
Year 2								
DC1	0	0	0	0	0	354	0	354
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**354**	**0**	**354**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	354	0	354
Total	**0**	**0**	**0**	**0**	**0**	**354**	**0**	**354**
Year 4								
DC1	0	0	0	0	0	354	0	354
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**354**	**0**	**354**

Table 67 Flows transported from the distribution centers to CZ6 by product and in each time period for SVA full-model.

	CZ7							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	155	0	205	0	0	0	360
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**155**	**0**	**205**	**0**	**0**	**0**	**360**
Year 2								
DC1	0	155	0	205	0	0	0	360
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**155**	**0**	**205**	**0**	**0**	**0**	**365**
Year 3								
DC1	0	156	0	205	0	0	0	361
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**156**	**0**	**205**	**0**	**0**	**0**	**361**
Year 4								
DC1	0	156	0	206	0	0	0	362
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	0	0	0
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**156**	**0**	**206**	**0**	**0**	**0**	**362**

Table 68 Flows transported from the distribution centers to CZ7 by product and in each time period for SVA full-model.

	CZ8							
Year 1	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	0	0	172	0	172
DC4	0	0	0	192	0	22	0	214
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**192**	**0**	**194**	**0**	**386**
Year 2								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	6	0	94	0	100
DC3	0	0	0	0	0	100	0	100
DC4	0	0	0	186	0	0	0	186
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**192**	**0**	**194**	**0**	**386**
Year 3								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	192	0	194	0	386
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**192**	**0**	**194**	**0**	**386**
Year 4								
DC1	0	0	0	0	0	0	0	0
DC2	0	0	0	0	0	0	0	0
DC3	0	0	0	192	0	194	0	386
DC4	0	0	0	0	0	0	0	0
DC5	0	0	0	0	0	0	0	0
DC6	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**192**	**0**	**194**	**0**	**386**

Table 69 Flows transported from the distribution centers to CZ8 by product and in each time period for SVA full-model.

Year	PL1							
	P1	P2	P3	P4	P5	P6	P7	Total
1	100	2 088	1 096	1 049	0	299	549	**5 181**
2	0	1 646	0	6	0	0	316	**1 968**
3	0	1 646	0	6	0	0	316	**1 968**
4	0	1 646	0	6	0	0	316	**1 968**

Table 70 Inventory quantities at PL1 by product and in each time period for SVA full-model.

Year	PL2							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	1198	0	908	691	0	542	**3339**
2	0	1198	0	908	691	0	542	**3339**
3	0	1198	0	908	691	0	542	**3339**
4	0	1198	0	908	691	0	542	**3339**

Table 71 Inventory quantities at PL2 by product and in each time period for SVA full-model.

Year	PL3							
	P1	P2	P3	P4	P5	P6	P7	Total
1	838	656	579	408	0	133	313	**2 927**
2	469	356	0	0	0	0	53	**878**
3	469	356	0	0	0	0	53	**878**
4	469	356	0	0	0	0	53	**878**

Table 72 Inventory quantities at PL3 by product and in each time period for SVA full-model.

Year	W1							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
1	5	19	60	30	0	41	10	**165**
2	0	0	0	0	0	0	0	**0**
3	0	0	0	0	0	0	0	**0**
4	0	0	0	0	0	0	0	**0**

Table 73 Inventory quantities at W1 by product and in each time period for SVA full-model.

Year	W2							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
1	0	159	650	312	226	638	91	2 076
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0

Table 74 Inventory quantities at W2 by product and in each time period for SVA full-model.

Year	W3							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
1	16	13	24	17	0	23	11	**104**
2	0	0	0	0	0	0	0	**0**
3	0	0	0	0	0	0	0	**0**
4	0	0	0	0	0	0	0	**0**

Table 75 Inventory quantities at W3 by product and in each time period for SVA full-model.

Year	W4							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Total**
1	0	0	0	14	0	0	0	**14**
2	0	0	0	0	0	0	0	**0**
3	0	0	0	0	0	0	0	**0**
4	0	0	0	0	0	0	0	**0**

Table 76 Inventory quantities at W4 by product and in each time period for SVA full-model.

Year	DC1							
	P1	P2	P3	P4	P5	P6	P7	Total
1	2	7	29	13	0	19	3	**73**
2	215	312	683	411	0	555	87	**2 263**
3	166	156	495	206	0	454	87	**1564**
4	0	0	0	0	0	0	0	**0**

Table 77 Inventory quantities at DC1 by product and in each time period for SVA full-model.

Year	DC2							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	2	5	4	3	4	1	**19**
2	0	107	231	206	153	0,00	63	**760**
3	0	53	115	103	76	0	32	**379**
4	0	0	0	0	0	0	0	**0**

Table 78 Inventory quantities at DC2 by product and in each time period for SVA full-model.

Year	DC3							
	P1	P2	P3	P4	P5	P6	P7	Total
1	5	4	4	0	0	8	3	**24**
2	0	212	0	423	0	385	186	**1 206**
3	0	106	0	307	0	289	97	**799**
4	0	0	0	0	0	0	0	**0**

Table 79 Inventory quantities at DC3 by product and in each time period for SVA full-model.

Year	DC4							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	1	8	0	0	0	**9**
2	116	0	308	192	0	194	80	**890**
3	0	0	0	0	0	0	0	**0**
4	0	0	0	0	0	0	0	**0**

Table 80 Inventory quantities at DC4 by product and in each time period for SVA full-model.

Year	DC5							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	0	0	0	0	0	0
2	0	0	619	0	0	0	0	619
3	0	0	310	0	0	0	0	310
4	0	0	0	0	0	0	0	0

Table 81 Inventory quantities at DC5 by product and in each time period for SVA full-model.

Year	DC6							
	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	354	0	354
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0

Table 82 Inventory quantities at DC6 by product and in each time period for SVA full-model.

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