INTEGRATION OF FINANCIAL ISSUES IN THE OPTIMAL DESIGN OF SUPPLY CHAIN NETWORKS

by **Pantelis I. Longinidis**

A Thesis
Submitted in Fulfilment of the Requirements
for the Degree of Doctor of Philosophy

Department of Engineering Informatics & Telecommunications
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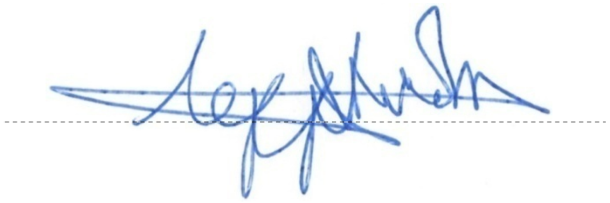

Pantelis I. Longinidis

MSc in Informatics & Management (Business Intelligence expertise),
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Contents

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The present PhD Thesis is the result of four years of hard work. Numerous academic articles have passed over my eyes, numerous models have been implemented and run in the GAMS tool, and numerous hours have been consumed in reading, writing, and thinking. My long journey started on 2009 when I decided to make the first required step in order to participate and to contribute to the academic community by specializing into a field. Now, ***"the boat has arrived successfully into the port and is ready for the next journey"***.

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I recognise that this research would not have been possible without the financial support of the "The Alexander S. Onassis Public Benefit Foundation" under the fellowship code G ZD 037-2/2011-2012. I am proud to be a scholar of the most prestigious and competitive public benefit foundation in Greece that has connect its history with a broad spectrum of projects related to culture, education, the environment, health, and social solidarity.

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Pantelis I. Longinidis

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List of Abbreviations

AI	Artificial Intelligence
AIT	Analytical Information Technology
APS	Advanced Planning System
BOM	Bill of Materials
CPFR	Collaborative Planning and Forecasting Replenishment
DRP	Distribution Resource Planning
ERP	Enterprise Resource Planning
EVA™	Economic Value Added™
EVPI	Expected Value of Perfect Information
FM	Financial Model
GAAP	Generally Accepted Accounting Principles
GAMS	General Algebraic Modelling System
GIS	Geographic Information Systems
GSCN	Global Supply Chain Network
IP	Integer Programming
IPO	Initial Public Offering
IT	Information Technology
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
MIP	Mixed Integer Programming
moMILP	Multi-objective Mixed Integer Linear Programming

moMINLP	Multi-objective Mixed Integer Non Linear Programming
MPC	Model Predictive Control
MRP	Material Requirement Planning
NFM	Non Financial Model
OR	Operations Research
POS	Point of Sales
RMU	Relative Money Units
SC	Supply Chain
SCM	Supply Chain Management
SCN	Supply Chain Network
SCND	Supply Chain Network Design
SCNE	Supply Chain Network Execution
SCNM	Supply Chain Network Management
SCNO	Supply Chain Network Operation
SEO	Secondary Public Offering
SKU	Stock Keeping Unit
SLB	Sale and Leaseback
TIT	Transactional Information Technology
TMS	Transportation Management Systems
WACC	Weighted Average Cost of Capital
WMS	Warehouse Management Systems

Abstract

Financial issues are among the most advanced and emerging modelling aspects within recent SCNs. As a result of diminishing profit margins and competitive landscape SCN managers are forced to optimise the design and operation of their SCNs by taking into account not only cost key performance indexes but also financial performance figures. Consequently, SCN managers are in the need of holistic decision support models that track and quantify the financial impact of their production and distribution decision by integrating various financial performance and financial attractiveness modelling frameworks. Integration of these frameworks in SCN models allow for the systematic assessment of the impact of production and distribution decisions in the financial performance and in the financial attractiveness and further selects their ideal combination thus providing a competitive advantage. Moreover, this integration bridges the gap and conflicts of interests between SCN managers and financial managers because it uses a "common language" between them and promotes constructive cooperation between them. As the final acceptance of an investment project is mainly decided by financial managers, a capital budgeting proposal, such as the establishment/restructure of the company's SCN, employing financial figures and indexes and making clear to these managers the effect of this project on financial performance and attractiveness, has more possibilities to be accepted.

This Thesis considers the development of SCN design models that integrate financial matters providing support to SCN managers in holistic decision making. In the first model a generic multi-echelon, multi-product, multi-period SCN design formulation is presented with time varying product demand uncertainty being its main novelty. Integration of financial statement analysis is the key feature of the second proposed SCN design model whereas credit solvency is the novel aspect of the third presented SCN design model. The key aspect of the last introduced SCN design model is the sale and leaseback of fixed assets technique.

Abstract in Greek

Οι χρηματοοικονομικές παράμετροι είναι μεταξύ των πιο εξελιγμένων και αναδυόμενων θεμάτων μοντελοποίησης στα σύγχρονα δίκτυα εφοδιαστικών αλυσίδων (ΔΕΑ). Ως αποτέλεσμα των μειωμένων περιθωρίων κέρδους και του ανταγωνιστικού περιβάλλοντος τα διοικητικά στελέχη που ασχολούνται με τα ΔΕΑ ωθούνται να βελτιστοποιήσουν τον σχεδιασμό και την λειτουργία των ΔΕΑ τους λαμβάνοντας υπόψη όχι μόνο δείκτες απόδοσης που προσανατολίζονται στο κόστος αλλά και δείκτες χρηματοοικονομικής απόδοσης. Συνεπώς, τα διοικητικά στελέχη που ασχολούνται με τα ΔΕΑ χρειάζονται ολοκληρωμένα μοντέλα στήριξης αποφάσεων τα οποία ανιχνεύουν και ποσοτικοποιούν την χρηματοοικονομική επίδραση των αποφάσεων τους για παραγωγή και διανομή μέσω της ενσωμάτωσης διαφόρων πλαισίων μοντελοποίησης της χρηματοοικονομικής απόδοσης και της χρηματοοικονομικής ελκυστικότητας. Η ενσωμάτωση αυτών των πλαισίων στα μοντέλα ΔΕΑ επιτρέπει την συστηματική αξιολόγηση της επίδρασης των αποφάσεων παραγωγής και διανομής στην χρηματοοικονομική απόδοση και ελκυστικότητα και επιπρόσθετα επιλέγει τον ιδανικό συνδυασμό τους με αποτέλεσμα να παρέχεται ένα ανταγωνιστικό πλεονέκτημα. Επιπλέον, αυτή η ενσωμάτωση γεφυρώνει το χάσμα και μειώνει την σύγκρουση συμφερόντων μεταξύ των διοικητικών στελεχών που ασχολούνται με τα ΔΕΑ και τα στελέχη που ασχολούνται με τα χρηματοοικονομικά επειδή χρησιμοποιεί μια κοινή γλώσσα μεταξύ τους και προάγει την εποικοδομητική συνεργασία μεταξύ τους. Καθώς η τελική απόφαση για την έγκριση μιας επένδυσης λαμβάνεται από τα στελέχη που ασχολούνται με τα χρηματοοικονομικά, ένας προϋπολογισμός πάγιων επενδύσεων, όπως η δημιουργία/αναδιάρθρωση του ΔΕΑ μια εταιρείας, ο οποίος περιλαμβάνει χρηματοοικονομικά μεγέθη και δείκτες που δείχνουν ξεκάθαρα στα στελέχη που ασχολούνται με τα χρηματοοικονομικά την επίδραση αυτής της επένδυσης στην συνολική χρηματοοικονομική απόδοση και ελκυστικότητα, έχει περισσότερες πιθανότητες να γίνει αποδεκτός.

Αυτή η διατριβή εξετάζει την δημιουργία μοντέλων σχεδιασμού ΔΕΑ που ενσωματώνουν χρηματοοικονομικά θέματα και παρέχουν στήριξη στα στελέχη διοικητικά στελέχη που ασχολούνται με τα ΔΕΑ για την λήψη ολοκληρωμένων απο-

φάσεων. Στο πρώτο μοντέλο παρουσιάζεται ένα γενικό πλαίσιο σχεδιασμού ΔΕΑ με πολλαπλά διαζώματα, πολλαπλά προϊόντα, και πολλαπλές περιόδους το οποίο έχει ως κύριο καινοτόμο του στοιχείο την αβέβαιη και χρονικά μεταβαλλόμενη ζήτηση των προϊόντων. Η ενσωμάτωση της ανάλυσης των χρηματοοικονομικών καταστάσεων είναι το καινοτόμο στοιχείο του δεύτερου προτεινόμενου μοντέλου σχεδιασμού ΔΕΑ ενώ η πιστοληπτική φερεγγυότητα είναι το καινοτόμο στοιχείο του τρίτου προτεινόμενου μοντέλου σχεδιασμού ΔΕΑ. Το κύριο στοιχείο του τελευταίου μοντέλου σχεδιασμού ΔΕΑ είναι η τεχνική της πώλησης και επαναμίσθωσης των πάγιων περιουσιακών στοιχείων.

CHAPTER 1

Introduction

1.1 Justification of the research theme

Supply Chain Management (SCM) has become a business concept of strategic importance for synchronous companies. Efficiency and effectiveness in SCM initially ensures sustainability and then profitability, growth and competitiveness (Bernardes & Zsidisin, 2008; Chen, Paulraj, & Lado, 2004; Hult, Ketchen, & Arrfelt, 2007; Kähkönen & Lintukangas, 2012; Lao, Hong, & Rao, 2010; Li, Ragu-Nathan, Ragu-Nathan, & Subba Rao, 2006; Shin, Collier, & Wilson, 2000; Tan, Kannan, Handfield, & Ghosh, 1999; Tracey, Lim, & Vonderembse, 2005). The developments that have driven to this condition concern mainly the expansion and intensification of competition in both the production and the supply side of products and services.

In specific, companies are competing in a global arena in order to gain raw materials, human resources, and know-how that will enable them to produce their products and services. In a similar manner, they are competing in order to supply their products and services in the final consumers. In both of the above rivalry cases the pure price competition is lacking and instead non price competition features are becoming more essential. Companies no longer choose their inputs (raw materials, human resources, and know-how) by having the price as their solely decision criterion but they evaluate other parameters such as quality of raw materials, flexibility in labour market, personnel expertise, capabilities of information technology (IT) integration with suppliers, financial sustainability of suppliers, etc. On the other hand, customers' purchasing behaviour is not motivated by having the price of the product or the service as the unique benchmark. Instead, customers prefer and they are willing to pay for continuously improved and tailored products and services that are capable of providing place convenience, waiting time convenience, delivery time convenience, and after sales convenience.

Companies should have the flexibility, speed, and responsiveness to satisfy the continuously changing customer requirements and needs regarding products and services and also to cope with the changing conditions regarding terms of inputs acquisition. A simple shift in the pricing policy yields short-term results but does not ensures anything for companies in the long run. In establishing flexibility, speed, and responsiveness numerous economic entities contribute essentially and they are not under the full control of the companies.

This competitive and complex business environment forced companies to manage their operations over the limited "unique enterprise" framework and to focus into their external environment in order to obtain the necessary sources and abilities (Spekman, Kamauff, & Myhr, 1998). Companies became more extravert and undertaken a more essential role in their relationships with all the economic entities, which were involved in the process of satisfying customer demand, from both the production side (relationships with supplier, relationships with suppliers' suppliers) and the supply side (wholesalers, retailers, customers). Moreover, companies realised that they cannot operate individually anymore but only as parts of a complicated business operation chain leading to the evolution of the term Supply Chain (SC) (Tan et al., 1999) . The importance of a SC system in achieving simultaneously a high level of efficiency, a high level of customer service and the ability to respond effectively to a changing environment is widely acknowledged (Beamon, 1999).

The SC is a dynamic network of collaboration consisted of many parties such as suppliers, manufacturers, transporters, warehouses, distribution centres, wholesalers, retailers, customers, etc. that are involved directly or indirectly in customer satisfaction process (Chopra & Meindl, 2004). The network of these parties is also called demand chain or value chain (Lambert, Emmelhainz, & Gardner, 1999). However, most SCs are actually networks of companies while both suppliers and wholesaler/retailers are multiple. Thus, the term Supply Chain Network (SCN) is more representative in describing the structure of most of the current SCs (Chopra & Meindl, 2004; Handfield & Nichols, 2002).

The cluster of companies and economic entities, which constitute a SCN, interact through continuous and two-sided connections and relationships that create and add value in products and services provided to the final consumer (Mentzer et al., 2001). The main processes taking place across a SCN are procurement from suppliers, transportation and warehousing of intermediate and final products, inventory management, distribution of products to wholesalers and/or to retailers, and delivery of products to final customers (Simchi-Levi, Kaminsky, & Simchi-Levi, 2000).

Figure 1-1 shows the structure of a typical SCN. For a company in the middle of the SC like a consumer goods manufacturer, the SC looks like an uprooted tree where the root system represents the supplier network and the branches of the tree represent the customer network. The SC will look different depending on a firm's position in it. For example, in the case of a retailer the consumers would be next to the red square in the centre of Figure 1-1 making them the only tier in the customer network. For an initial supplier, such as a shrimper, there would be no suppliers associated with product flow (Lambert, 2008).

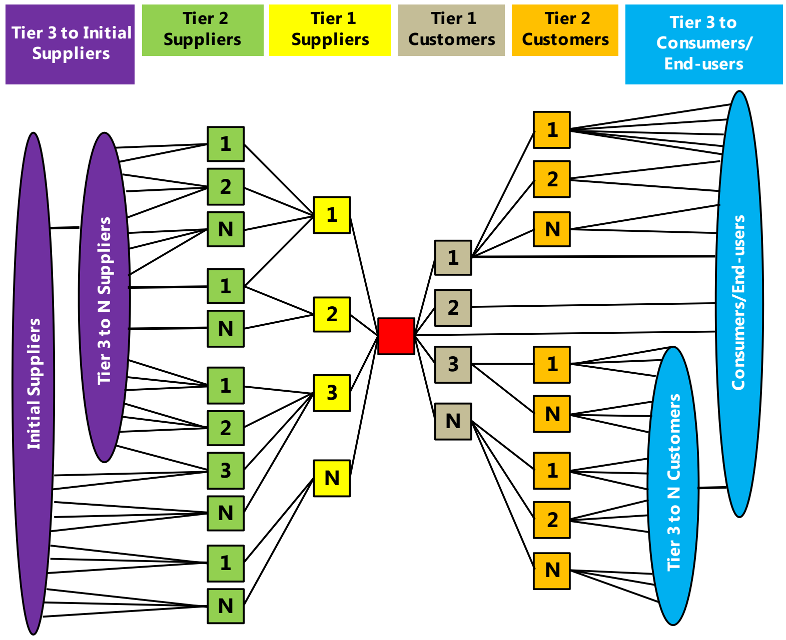


Figure 1-1: The structure of a SCN

Source: Lambert, D. M. 2008. Supply chain management. In D. M. Lambert (Ed.), ***Supply Chain Management: Processes, Partnerships, Performance***, 3rd ed.: 1-24. Sarasota, FL: Supply Chain Management Institute, p. 6.

The structure of a SCN can be viewed and studied via three perspectives: a) the perspective of an individual firm (e.g. the ZipCo's SCN), b) the perspective of a particular product or item (e.g. beef's SCN, OR coffee's SCN, or oil's SCN), and c) the perspective that considers SCN as a handy synonym for purchasing, distribution, and materials management (New, 1997). Additionally, a SCN is characterised by its vertical structure (width) and its horizontal structure (depth). The latter represents the number of tiers along the analytical scope of a SCN while the former represents the number of partners within each tier (Wang, Heng, & Chau, 2007).

The management of a SCN (SCNM) concerns the management of upstream and downstream relationships with suppliers and customers. These relationships are two-way and continual aimed at delivering superior customer value at less cost to the SCN as a whole (Christopher, 2005).

Figure 1-2 illustrates the entities that participate and the relationships that are developed in the framework of SCNM. These relationships concern information systems management, sourcing and procurement, production scheduling, order processing, inventory management, warehousing, customer service, and after-market disposition of packaging and materials. From the focal firm's perspective, the SCN includes upstream suppliers, internal functions, and downstream customers. A firm's internal functions include the processes used in transforming the inputs provided by the supplier network. Among all participating entities flows of information (arrows) and flows of products, services, funds, and knowledge (dotted arrows) taking place in order to satisfy end consumer's demand and thus and integrated SCN is created (Handfield & Nichols, 2002).

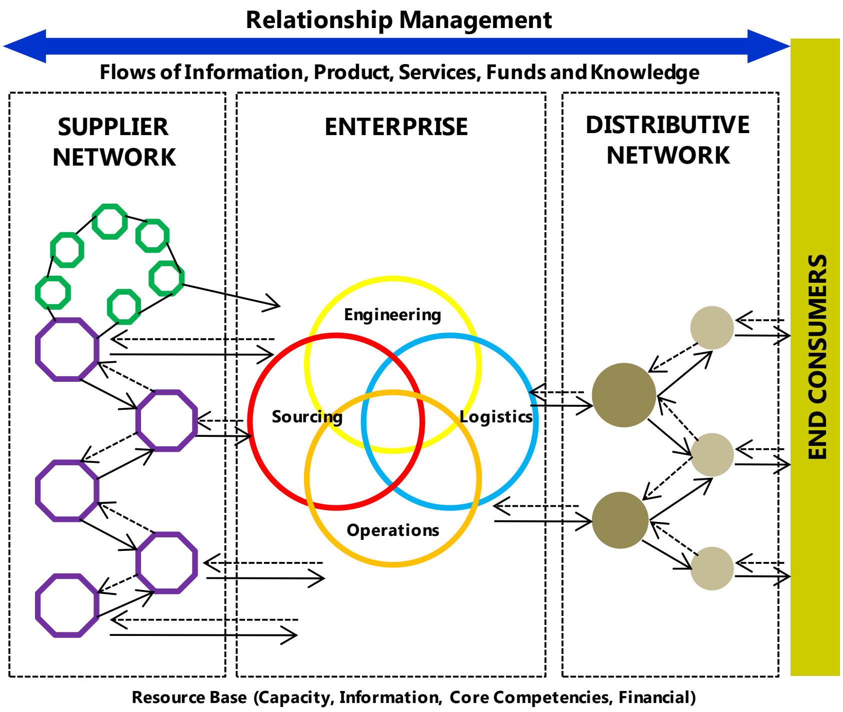


Figure 1-2: The integrated SCN

Source: Handfield, R. B., & Nichols, E. L., Jr. 2002. ***Supply Chain Redesign: Transforming Supply Chains into Integrated Value Systems***. Upper Saddle River, NJ: FT/Prentice-Hall, p. 9.

The objective of SCNM is to maximise the overall value generated within the SCN. This value is the difference between what the final product worth to the customer and the effort the SCN expends in filling the customer's request (Chopra & Meindl, 2004). Each company should define its SCNM objectives in accordance to its corporate objectives. For each one of these higher level targets a set of detailed goals should particularise, for every process taking place within the SCN, the way of achieving and evaluating the desired result. This cascading method serves to integrate the SCN processes with the overall enterprise direction and further to avoid undesirable conditions caused by conflicting targets of individual departments or functions (Cohen & Roussel, 2005; Lummus & Vokurka, 1999).

A salient factor in defining targets and in evaluating degree of achievements is the perspective through which the SCNM is approached. The fact that, by definition, SCNM encompasses and integrates so many diverse, and in many cases competitive, processes and functions makes difficult the single-dimensional analysis and leads to several approaching perspectives. Otto and Kotzab (2003) identified in literature six important SCNM analysis perspectives. Table 1-1 summarises these perspectives along with their core objective and focus area of improvement.

It is clear form Table 1-1 that each perspective has its own objectives and focus areas. An integrated SCNM system should be capable to consider all these perspectives and to achieve all objectives simultaneously. However, the complexity of simultaneous goal optimisation and the conflicts among different goals makes difficult the development of models that integrate all the above objectives. Consequently, research is focusing in specific perspectives with the aim to create models that optimise their corresponding objectives.

Table 1-1: SCNM objectives under different perspectives

Perspective	Core objective	Improvement focus area
System Dynamics	Managing trade-offs along the complete supply chain	Order management
Operations Research	Calculating optimal solutions within a given set of degrees of freedom	Network configuration and flow
Logistics	Integrating generic processes sequentially, vertically, and horizontally	Integration of processes
Marketing	Segmenting products and markets and combine both using the right distribution channel	Fit between product, channel and customer
Organisation	Determining and mastering the need to coordinate and manage relationships	Intra-enterprise segmentation
Strategy	Merging competencies and re-locating into the deepest segments of the profit pool	Ability to partner; positioning in the chain

The Operations Research (OR) perspective is one of the most interesting perspectives as many of its tools, methodologies, and techniques had been utilised since the early days of SCNM and are continue to gain popularity, in tackling problems arisen during SCNM implementation, hitherto. The seminal contributions of Geoffrion and Graves (1974), Williams (1981, 1983), Cohen and Lee (1988), Roy (1989), and Lee and Billington (1993) employed OR methodologies and developed mathematical models that integrate several functions of a SCN seeking to optimise its operation. OR on the SCNM can be divided into three primary approaches to conducting SCN modelling, namely: optimisation, simulation, and heuristics (Ivanov & Sokolov, 2010).

The OR perspective models the SCN as configurable and flow-programmable resource network, which has the function of moving (primarily) material objects from the sources of production to end customers, thereby adhering to various restrictions. The OR perspective becomes relevant to SCNM, if the supply chain offers short-, medium- or long-term optimisation potentials; for example, if a variation in the allocation of customers and distributions centres reduces distribution costs or increases customer satisfaction. Elements within the optimisation scope may be plants, distribution centres, suppliers, customers, orders, products, or inventories (Otto & Kotzab, 2003).

The standard problems within the OR perspective are presented in Table 1-2 and formulated in the following manner. A set of goals should be achieved by minimising the costs of transfer and transformation. In partial solutions, particular goals are selected, like to secure a certain service level, to minimise lead time, to maximise capacity utilization, or to secure availability of resources. The standard solutions in the OR perspective can be found in the establishment of certain algorithms, which identify the optimal solution for the problems (Otto & Kotzab, 2003).

Table 1-2: Typical SCNM problems via Operations Research perspective

Standard problems	Description
Manufacturing	How many plants are necessary? Which degree of integration is best? What products should be produced in which plants? What are the additional costs of mirroring production? Do tax advantages in a particular country compensate the additional freight charges?
Distribution/transportation	How many distribution centres should be set up? Which customers should be served out of which distribution centre? Which transportation mean should be used for serving the distribution centres and customers?
Supplier	Which suppliers should supply which products to which plants?
Spare parts	Which product design minimises the costs of securing spares availability? How many repair centres should be maintained and which returns should be directed to which centres? Which spare part should be kept on inventory (level and place)?

One way of classifying SCNM analysis is to divide the area into SCN design (SCND) and SCN operation (SCNO) or execution (SCNE). The former is the process of determining the supply chain infrastructure (e.g. plants, warehouses, distribution centres, transportation modes and lanes, production processes, etc.) that will be used to satisfy customer demands. These studies are strategic in scope, use a time horizon of months or years, and typically assume little or no uncertainty with the data. The latter is the process of determining solutions to more tactical issues such as local inventory polices and deployment, manufacturing and service schedules, transportation plans, etc. In these instances, production and transportation data are usually assumed to vary according to a known probability distribution. The time period for the analysis typically spans days or weeks, and focuses on implementing detailed short-term plans (Harrison, 2001). The SCNO decisions are further divided into tactical, with a time horizon spanning from days to months, and operational, with a time horizon spanning from hours to days (Huan, Sheoran, & Wan, 2004).

Figure 1-3 illustrates a five-phase hierarchical process for SC decision-making integration, the general time horizon for implementation, the frequency of occurrence, and the linking of the phases by a common database. The five phases are grouped into planning and control levels, recognizing the functional distinction between planned operations versus actual flow control of materials. The "Supply Chain Design" phase establishes the overall configuration of the network by determining the number of facilities, distribution centre locations, transportation modes, product design, vendor support, etc. "Aggregate Supply Planning" establishes general resource levels for the different stages for the annual business planning period. For example, manufacturing and service centre workforce levels would be set, transportation fleet deployment would be decided, and purchasing agreements would be reviewed. "Material Flow Planning" establishes a variety of time-phased schedules such as material from vendors through inbound logistics, inventory position levels at warehouses and distribution centres, production requirements in plants, and distribution shipping schedules. "Order Fulfilment" focuses upon the allocation of material for production and shipping, based upon received and released orders between the stages in the chain. And finally, the continuous activity of "Scheduling/Dispatching" concentrates upon the real-time sequencing of material through work centres, the release of material from the vendor, and dispatching service personnel to repair equipment. If these five stages are performed in an integrated manner, they must share a common database that is updated as changes occur over time (Mabert & Venkataramanan, 1998).

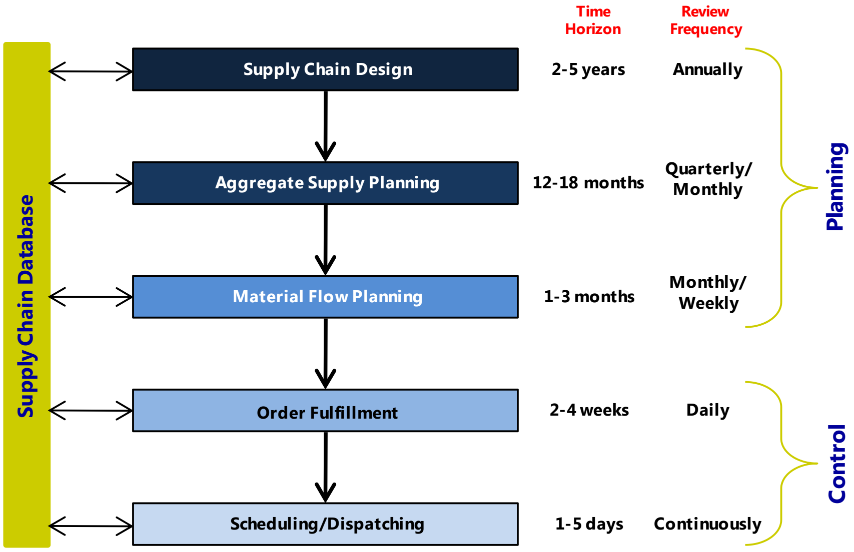


Figure 1-3: The SCN decisions

Source: Mabert, V. A., & Venkataramanan, M. A. 1998. Special research focus on supply chain linkages: challenges for design and management in the 21st century. ***Decision Sciences***, 29(3): 537-552.

Min and Zhou (2002) conduct an interesting taxonomy of the many and different SCNM models found scattered across various studies. As shown in Figure 3-4, the authors classified SCNM models into four major categories: (1) deterministic (non-probabilistic); (2) stochastic (probabilistic); (3) hybrid; (4) IT-driven. Deterministic models assume that all the model parameters are known and fixed with certainty, whereas stochastic models take into account the uncertain and random parameters. Deterministic models are dichotomised as single objective and multiple objective models. Stochastic models are sub-classified into optimal control theoretic and dynamic programming models. Hybrid models have elements of both deterministic and stochastic models. These models include inventory-theoretic and simulation models that are capable of dealing with both certainty and uncertainty involving model parameters. IT-driven models aim to integrate and coordinate various phases of supply chain planning on a real-time basis using application software so that they can enhance visibility throughout the supply chain. These models include Warehouse Management Systems (WMS), Transportation Management Systems (TMS), integrated transportation tracking, Collaborative Planning and Forecasting Replenishment (CPFR), Material Requirement Planning (MRP), Distribution Resource Planning (DRP), Enterprise Resource Planning (ERP), and Geographic Information Systems (GIS).

Other taxonomies of SCNM models classify them to: (1) analytical models (e.g. robust optimisation, stochastic programming, games theory, Linear Programming (LP) and parametric programming); (2) models based on Artificial Intelligence (AI) (e.g. multi-agent system, fuzzy linear programming, fuzzy multi-objective programming, fuzzy goal programming, fuzzy numbers, reinforcement learning, evolutionary programming and genetic algorithms); (3) simulation models (e.g. discrete even simulation and system dynamics); (4) hybrid models (e.g. LP and simulation, Model Predictive Control (MPC), stochastic dynamic programming, Mixed Integer Linear Programming (MILP) and discrete event simulation, genetic algorithms and simulation) (Peidro, Mula, Poler, & Lario, 2009). Respectively, Beamon (1998) categorises these models into: (1) deterministic analytical models, in which the variables are known and specified; (2) stochastic analytical models, where at least one of the variables is unknown, and is assumed to follow a particular probability distribution; (3) economic models; and (4) simulation models.

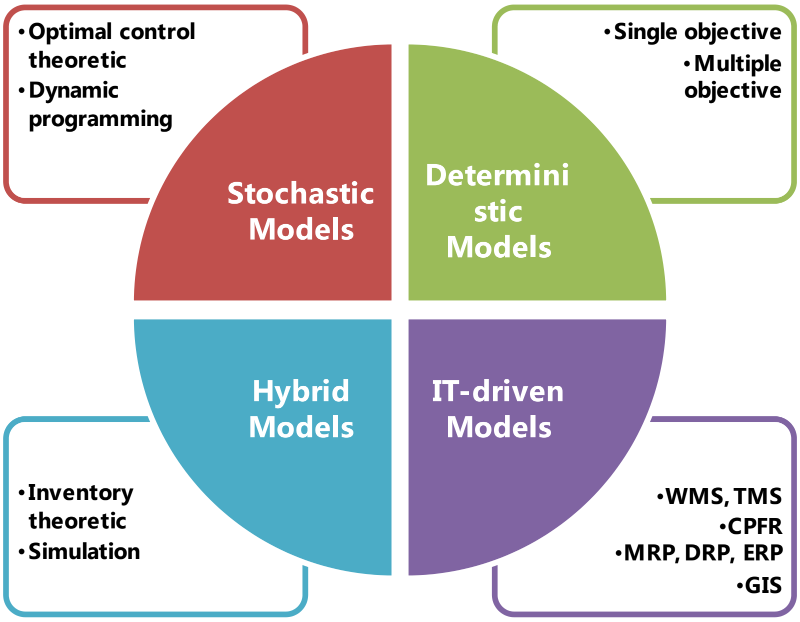


Figure 1-4: A taxonomy of SCNM models

Source: Min, H., & Zhou, G. 2002. Supply chain modelling: past, present and future. ***Computers & Industrial Engineering***, 43(1-2): 231-249.

The research stream of SCNM flourish in the 1990’s due to advances in IT. To effectively apply IT in managing SCN, a company must distinguish between the form and function of Transactional IT (TIT) and Analytical IT (AIT). TIT is concerned with acquiring, processing and communicating raw data about the company’s past and current SCN operations, and with the compilation and dissemination of reports summarizing these data. Typical examples are Point of Sales (POS) recording systems, general ledger systems, quarterly sales reports, and ERP. In contrary, AIT evaluates SCN decisions based on models constructed from SCN decision databases, which are largely, but not wholly, derived from the company’s transactional databases. It is concerned with analyzing decisions over short-, medium-, and long-term futures. Typical examples of this type of IT are modelling systems for scheduling weekly production, forecasting demand for next month and allocating it to manufacturing facilities, or locating a new distribution centre. The critical elements of AIT are mathematical programming models. These models can unravel the complex interactions and ripple effects that make SCNM difficult and important. They are the only analytical tools capable of fully evaluating large numerical data bases to identify optimal, or demonstrably good, plans. They can also measure tradeoffs among cost or revenues and service, quality and time. Linear and Mixed Integer Programming (MIP) models are the types most commonly used for SCNM problems. In practice, MIP models are best combined with approximation and heuristic methods, especially for scheduling applications (Ivanov & Sokolov, 2010; Shapiro, 1999a).

LP is the cornerstone of mathematical programming because LP models can be easily optimised and because LP approximations are used to optimise more complex models. The premises underlying LP models, such as assumptions that all cost and resource utilization relationships are linear and infinitely divisible, are too simplistic. MIP extensions provide a much more realistic description of SCNM problems. Such models use zero-one integer variables to describe more accurate cost and resource relationships, and to capture locational decisions. The added realism of MIP is achieved at a cost because such model must be optimised as a series of LP approximations. Despite their computational complexity, MIP models are a practical and powerful method for evaluating SCN. Comprehensive MIP models can be rapidly and reliably optimised on today's platforms (Shapiro, 1999b).

SCN managers should realise that the development of accurate descriptive models is necessary but not sufficient for realizing effective decision making. For example, accurate demand forecasts must be combined with other data in constructing a global optimisation model to determine which plants should make which products to serve which distribution centres and markets so that demand is met at minimal SCN cost. Similarly, an accurate management accounting model of manufacturing process costs is necessary but not sufficient to identify an optimal production schedule (Shapiro, 2001).

Since companies recognised the potential competitive advantages, gained through a holistic management of their SCNs, the academic community has been developing several models that describe their design and operation. These models support management staff in both strategic and tactical/operational decisions regarding management of supply and distribution networks.

It was recognised early on that systematic, optimisation-based approaches should be used, and that “common-sense” heuristics might lead to poor solutions in distribution planning (Geoffrion & Van Roy, 1979). These early models tended to focus on the logistics aspects. Clearly, much more benefit could be achieved by simultaneously considering the production aspects and other issues related to integration of inventory, transportation, supplier selection, and investment budgeting decisions (Melo, Nickel, & Saldanha Da Gama, 2006). Analytical and simulation models that integrate the three major stages of SCNs (supply network, plants, distribution) is an important future direction of research in this area (Erengüç, Simpson, & Vakharia, 1999).

Although numerous successful models have been developed for the design and operation of SCNs, their vast majority ignores decisions involving revenues, marketing campaigns, hedging against uncertainties, investment planning and other corporate financial decisions (Comelli, Féniès, & Tchernev, 2008; Gupta & Dutta, 2011; Klibi, Martel, & Guitouni, 2010; Laínez, Reklaitis, & Puigjaner, 2010; Shapiro, 2004).

Furthermore, various international trade factors related to financial management, such as exchange rates, taxes, quotas, and tariffs, are not adequately described by existing models (Goetschalckx, Vidal, & Dogan, 2002; Vidal & Goetschalckx, 1997). Especially for global SCNs, variability and uncertainty in these factors increases their risks and affects their financial performance (Meixell & Gargeya, 2005). Integration of activities such as finance, marketing, new product development and customer service, differentiates SCNM from traditional logistics where the emphasis is given on activities such as procurement, distribution, maintenance, and inventory management (Hugos, 2003). Financial factors are among the issues that have a strong impact on the configuration of global supply chains (Melo, Nickel, & Saldanha-da-Gama, 2009). Financial globalization factors such as corporate income taxes, transfer prices, currency exchange rates, are some of the key components that a SC design model in the delocalization context should take into account (Hammami, Frein, & Hadj-Alouane, 2008). Integration of financial aspects in these models allows for the systematic assessment of the impact of production decisions in the financial operation and further selects their ideal combination thus providing a competitive advantage in the company (Gomm, 2010; Guillén, Badell, Espuña, & Puigjaner, 2006a; Hahn & Kuhn, 2012). Neglecting financial issues may have undesirable negative impacts for a firm, as it may lead to suboptimal or even infeasible overall plans for the whole SCN (Puigjaner & Guillén-Gosálbez, 2008a).

The aforementioned gap in existing literature has stimulated the research interest of this Thesis as it desires to fulfill the need to integrate various financial aspects in the mathematical models of SCN design.

1.2 Thesis scope

The main scope of this Thesis is to develop various mathematical programming models that are capable of expressing and monitoring several financial management aspects and parameters inherent in the design of SCNs. The significance of modelling SCN's operations such as financial management, negotiation with all SCN parties, human resource management, and others along with the core operations of production and distribution have been early recognised from several researchers. In essence, this conjunction satisfies the definition of SCNM where the emphasis is given in the holistic management of all functions taking place and all relations generated in order to begin the product from the source of the raw material and to arrive at the shelf of the sales centres.

Special interest will be given to how financial decisions interact with production and distribution decisions in order to find the trade-offs, if any, and further to find their optimal combination which maximises the total SCN added value. In these lines, the models will aim to express and monitor financial statement analysis, credit standing evaluation, sale and leaseback of fixed assets, and hedging against financial risks.

All aforementioned models will be either deterministic or stochastic. In the latter case, appropriate uncertainty modelling techniques will be implemented. LP and MILP will be the main mathematical programming techniques utilised in this Thesis. However, due to the non linear nature of most financial aspects, MINLP models will be also employed.

1.3 Thesis structure

The goals and objectives of this Thesis, which have been briefly stated in the previous section, delineate its structure as shown in Figure 1-5. In particular, Chapter 1 includes a brief justification of the Thesis' research theme along with an ambiguously definition of its scope and its individual objectives that will lead in achieving its core target.

Chapter 2 reviews the previous and current literature in the SCN modelling area. Starting from the pioneers of SCN modelling whose works have been a breakthrough in the field moves towards the current and emerging issues in SCN modelling by a chronological path that contains penetration of SCN modelling into companies and into industries. Special interest is given to the body of literature related to demand uncertainty and financial management as this Thesis aims to contribute to these areas.

Chapter 3 presents a basic SCN design model under uncertain and transient demand conditions. This is a MILP model with its main novelty being the modelling of an uncertain and time varying product demand profile. The main objective of this model is to find the optimal SCN's configuration so that the total cost along the SCN is minimised and the demand is satisfied. This is the general model that will be used in consequent chapters by integrating various financial issues.

Chapter 4 enriches the model presented in the previous chapter by incorporating a financial management aspect. In specific, a MILP model is developed with its two main novelties being both the modelling of financial statement analysis and the modelling of an uncertain and time varying product demand profile. The main objective of this model is to find the optimal SCN's configuration so that the total shareholders' Economic Value Added (EVA™) is maximised throughout the SCN and at the same time targeted financial status and product demand are both satisfied.

Chapter 5 presents a non linear version of the model introduced in Chapter 4. In particular, a multi objective Mixed Integer Non Linear Programming (moMINLP) model is developed with its three main novelties being: (1) the modelling of credit solvency through a multivariate index; (2) the modelling of economic uncertainty through scenario tree approach; (3) the modelling of the real cost of capital, a parameter utilised in almost all project appraisal methods. The two main objectives of this model is to find the optimal SCN's configuration and operation so that the total shareholders' Economic Value Added (EVA™) is maximised throughout the SCN and at the same time the credit standing is also maximised.

Chapter 6 introduces a MINLP model that integrates the Sale and Leaseback (SLB) technique within a generic SCN design model. SLB is an advanced financial management method that releases the value of real estate, improves balance sheet, and realises tax benefits. The main objective of this model is to find the optimal SCN's configuration and assets ownership status so that the Net Operating Profits After Taxes (NOPAT) and the Unearned Profit on SLB (UPSLB) are maximised.

Chapter 7 summarises the Thesis achievements and thus provides a holistic picture in order to justify whether it has fulfils its goals and targets. Future research directions and further investigation avenues are provided therein.

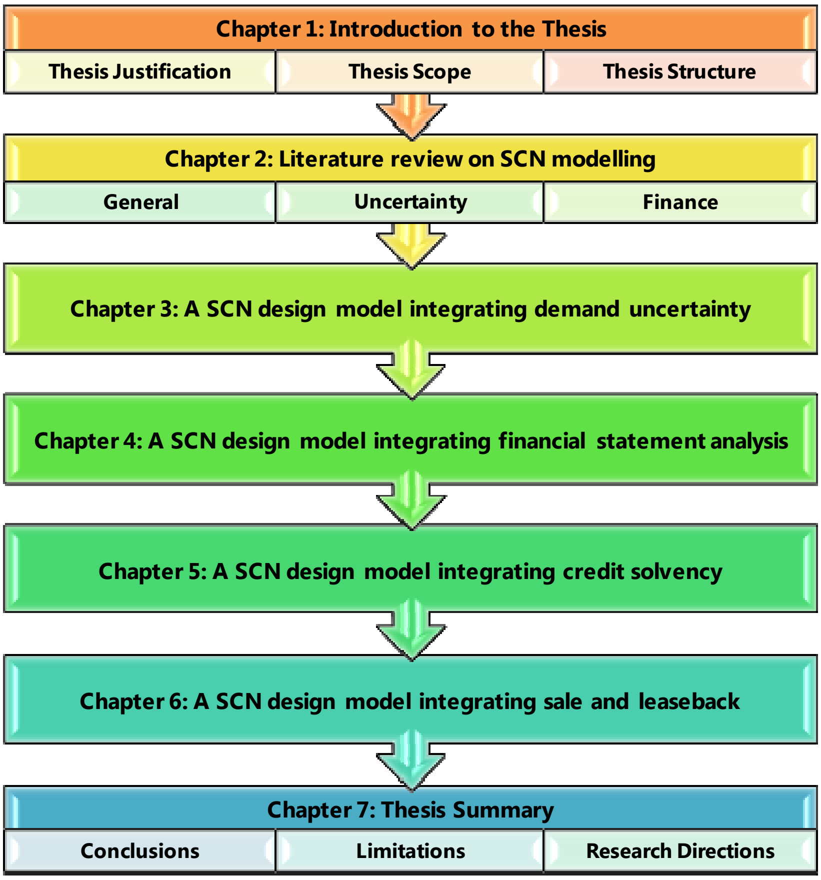


Figure 1-5: The structure of the PhD Thesis

CHAPTER 2

Literature review

2.1 Introduction

During the last decade, SCNM has become a field of great interest among academics and practitioners in the operations management field. A review of the articles published in Production and Operations Management, a leading journal published by the Production and Operation Management Society, strongly suggested that SCNM had become the dominant theme in operations management research (Kouvelis, Chambers, & Wang, 2006). On the other hand, a web search of the term "Supply Chain Management" returned seven millions results, a number almost double from the returned results for the term "Operations Research/Management Science" or "Inventory Management", and almost five times as much as the returned results for the term "Production Management" or "Materials Management"[1]. These indicate that SCNM is increasing its recognition and interest in both academic and non academic disciplines.

The universal recognition of SCNM lead to a vigorously growth in mathematical models aimed at optimising the SCND and the SCNO. These models have become a mainstream in the relevant literature and according to Sabri and Beamon (2000) are divided into strategic and operational. The primary objective of strategic optimisation models is to determine the most cost-effective location of facilities (plants and distribution centres), flow of goods throughout the SCN, and assignment of customers to distribution centres. These types of models do not seek to determine required inventory levels, and customer service levels. The main purpose of the optimisation in operational models is to determine the safety stock of each product at

[1] The web search was conducted by the author in October 10, 2009 with the search engine of Google Inc.

each location, the size and frequency of the product batches that are replenished or assembled, the replenishment transport and production lead times, and the customer service levels.

In this chapter a review of the past and present SCN modelling research contributions, in the fields where this Thesis has pointed its interest into, will be presented. In specific, Section 2.2 presents a historical flashback of the early and pioneer works in the SCN modelling area. Section 2.3 reviews the SCN modelling works which have incorporated uncertainty aspects followed by Section 2.4 which reviews the incorporation of various financial aspects within SCN modelling studies. Finally, concluding remarks are drawn in Section 2.7.

2.2 SCN modelling

The term SCN modelling refers to SCND and SCNO. These two aspects of modelling, either separately or together, have attracted the interest of researchers since the need of integrated production/distribution systems became a necessity in operations research literature. Theretofore, several models had been concerned with supply, production, inventory, and distribution activities but in an isolated manner.

According to Cohen and Lee (1988) the earliest attempt to build an analytical model containing material procurement, production, and distribution elements in an integrated manner was that of Hanssmann (1959). The model identified the optimal inventory levels at all potential locations of inventories in a production or distribution system. However, a number of simplifying assumptions made the model not feasible for realistic supply and distribution channel systems. An analogous model developed by Simpson (1958) treated the problem of finding the optimal inventory levels at all nodes of a production network but had similar drawbacks and shortcomings in expressing an integrated SCN.

2.2.1 The pioneers of SCN modelling

Essentially, research in this field started with the seminal paper of Geoffrion and Graves (1974) who presented an algorithm based on Benders decomposition to solve a multicommodity, single-period, production-distribution problem with several plants with known capacities, possible distribution centres and a number of customers zones. Fixed and variable costs for distribution centres, production costs, and linear transportation costs were included in the objective function. Capacity at plants, customer demand satisfaction, single sourcing by customer zone, bounds on the throughput at distribution centres, and linear configuration constraints on binary variables (logical constraints), were the main constraints considered in the model. The model aimed to optimise annualised finished product flows through the entire SC, which involved all the nodes from vendors to factories to warehouses to customers.

Vidal and Goetschalckx (1997) stated that probably this is the first comprehensive MIP model that tackles the integration issues within SCN modelling.

Geoffrion and co-workers continued their studies in this field and published several extensions and modifications of their initial model. On these lines, single sourcing of customer zone by commodity, non linear facility throughput constraints, and tradeoffs between distribution and customer service models were presented in Geoffrion et al. (1978). A final version on their initial model was presented in Geoffrion et al. (1982) with a more thorough description of the system and a more managerial emphasis, by deliberately excluding the technical aspects of optimisation. In this way the authors aimed to accommodate the broadest possible audience as in their first attempt to do so in Geoffrion and Powers paper (1980). Finally, Geoffrion's research group, as early originators of more than few distribution design models, summarised their experiences and communicate their findings in Geoffrion and Powers paper (1995), which aimed to highlight the benefits of integrated production/distribution network design.

After the pioneer model of Geoffrion and Graves (1974) other authors and research groups have developed analogous production/distribution models. Williams (1981) presented seven heuristic algorithms for production scheduling in an assembly network, distribution scheduling in an arborescence network, and joint production-distribution scheduling in a conjoined assembly-arborescence network. The objective of each algorithm was to determine a production and/or product distribution schedule which satisfies final product demand and minimises the sum of the average inventory holding costs and average fixed charges for processing (ordering, delivery, or setup costs), per period, over an infinite planning horizon. Exogenous demand for product was assumed to be deterministic, at a constant rate, and to occur only at "retail" facilities of the networks. The seven heuristic methods were compared with each other and with a dynamic programming algorithm on the basis of their performance in 11,000 computer generated problems. Managerial recommendations for the appropriateness of each heuristic for each network structure were made by the authors. In a consecutive paper, Williams (1983) presented a dynamic programming algorithm for simultaneous determination of production batch sizes in an assembly network and distribution batch sizes in a conjoined assembly-arborescence network distribution network. The objective was to minimise average cost per period over an infinite horizon. Costs consist of processing costs at each node and linear holding costs for inventory. Final product demand rates varied among the retail nodes, but at each retail node the demand rate was assumed to be known, constant, and continuous. The model could have been used for a single product, or for several products that were temporarily combined for distribution, or for scheduling production in a system where several end products were produced from the same intermediate product, as in some biochemical manufacturing processes.

Cohen and co-workers provided substantive contributions in the field where they extended the Geoffrion and Graves (1974) model by introducing various strategies to improve manufacturing operations in their model named PILOT (Cohen & Lee, 1985). PILOT was a deterministic, periodic (annual), MIP production/distribution model with a non linear objective function expressing costs. PILOT aimed to determine the number and allocation of plants and distribution centres, flows of materials (raw materials, intermediate, and finished products), production volumes in plants, and the allocation of customers to distribution centres. The model was consisted of two sub-models. The one that optimised the product flows from raw materials vendors to end customers and the other that emphasised to economies of scale in production. However, the technical details of PILOT in that paper were limited. In a later paper, Cohen and Lee (1988) presented a comprehensive modelling framework for linking decisions and performance throughout the material-production-distribution SC. The objective of the framework was to predict the impact, on performance, of alternative manufacturing and material strategies. A unified, hierarchical, stochastic, network model structure was developed having the following submodels, where each represents a part of the overall SC network: (1) material control; (2) production control; (3) finished goods stockpile; and (4) distribution network control. For each submodel there was a set of control parameters, such as lot sizes, reorder points, safety stock, etc., which were set so that the performance of the submodel meets some specific policy targets set for the submodel. Moreover, the control parameters set at one submodel affect the performance of another submodel. Each subproblem was optimised separately in a given sequence. The solution of a submodel was used as the input data to all other subproblems.

In two subsequent papers Cohen and co-workers focus their research attention to global production/distribution models. Initially, Cohen et al. (1989) provided a normative, dynamic, MINLP model that was differentiated from the single-country model by explicitly including vendor supply contracts, which leaded to the consideration of fixed vendor costs to opening contracts, and local content constraints, which required a minimum expenditure on production and raw materials acquisition within a particular country based on the level of sales in that country. The model was based on a three-level network, composed of vendors, plants and markets, without considering assembly, plant-to-plant transfers or warehousing. Its objective function was after-tax profits maximisation subject to constraints on material supply, material requirements, plant shipments, market demand, market cash flows, plant capacities and local content rules. The financial variables that determine the transfer pricing and the allocation of overhead costs to plants, resulted from fixed vendor costs, were the sources of non linearity in the model. Hence, the authors presented a heuristic method that firstly fixed transfer prices and allocated overhead cost and then transformed the model into a tractable MILP model. However, they did not provide sufficient evidence regarding computational experience from the model's implementation. In a simplified version of the aforementioned model Cohen and Lee (1989) presented a deterministic, single period MINLP model that was run sequentially over a specific time horizon in order to represent multiple time periods. The binary variables expressing different scenarios were fixed and the resulting LP models were then solved. A numerical example, demonstrating the application of their model to analyse tradeoffs involved in producing personal computers in an international network, was provided.

Cohen's research group continued its contributions in the filed with Cohen and Moon (1990, 1991) work, where they used initially the PILOT, to investigate the effects of various variables (unit transport costs and plant fixed costs) on the optimal SC structure, and thereupon they provided a new formulation of a class of plant product mix-loading problems which were characterised by fixed facility costs, concave production costs and an integrated network structure which encompassed inbound supply and outbound distribution flows. The proposed MINLP model captured both scale and scope economies and considered cost tradeoffs throughout the various stages of the SC. A piecewise concave cost function was used to capture scale economy effects and fixed costs of product assignment served to capture diseconomies of scope (i.e., the cost of complexity or the degree of flexibility at the plants). The authors developed an optimisation algorithm within the framework of Benders decomposition for the case of a piecewise linear concave cost function. The algorithm generated optimal solutions efficiently and also the problem solutions illustrated model's effectiveness in evaluating tradeoffs between inbound, production and outbound costs.

Directly following the previously mentioned works of Cohen and Moon (1990, 1991), Cohen and colleagues focused on the management of materials within an integrated SC. Along these lines, Pyke and Cohen (1993) presented a Markov chain model of a basic, single-product, three-node production-distribution system which was consisted of a single station model of a factory, a finished goods stockpile, and a single retailer. Due to the size of the state space of the Markov chain, they developed an alternative method for obtaining steady state distributions for key random variables (stock on hand at the beginning of the cycle, stock level at the beginning of the period, the size of an expedite batch, the undershoot of the reorder point, the undershoot of the expedite reorder point, etc.) which determined system performance. The final constrained optimisation model aimed to minimise the total cost within the SC subject to service levels constraints. In Pyke and Cohen (1994) the previous model was extended by considering multiple product kinds instead of a single product.

2.2.2 The penetration of SCN modelling in companies

As companies had begun to realise the emerging importance of integrated procurement/production/distribution analysis many research groups were concerned with real life problems faced by these companies. On these lines, Brown et al. (1987) developed a MILP model that was used by NABISCO in order to manage complex problems involving facility selection, equipment location and utilization, and manufacture and distribution of products. The objective function incorporated variable production and shipping costs, fixed costs of equipment assignment (facilities to plants), and fixed costs of plant operations. Customer demand satisfaction constraints, balance constraints, multi-product capacity constraints, maximum number of facilities (equipment) assigned to each plant, single sourcing of facilities to plants, and upper bounds on products produced on each equipment at each plant were included in the model. A decomposition technique, with production goal constraints added to the master problem, was employed in order to solve the problem. Robinson et al. (1993) developed a MILP model for designing a two-echelon, multiproduct, uncapacitated facility location and distribution system and they applied it to a problem faced by DowBrands, Inc. The objective function represented the fixed costs for establishing central distribution centres and regional distribution centres and the variable costs for serving customers. Sensitivity analysis, cost service trade-offs, and what-if analysis accompanied the verification of the model's data and code. Davis (1993) worked with Hewlett-Packard and developed a framework for dealing with uncertainty that adversely affected performance of supplier, manufacturing, and transportation processes within its SCN. However, the author did not provide adequate information regarding the modelling techniques that had been applied. Lee et al. (1993) developed an inventory model used to evaluate alternative product and process designs for localization of a printer division in Hewlett-Packard's SC. The two design alternatives were "factory localization", where all the manufacturing-assembly processes took place in the factory and follow the upstream SC, and "distribution centre localization", where a module is assembled in distribution centres and then follow the upstream SC. The analysis indicated that the shift from the former to the latter design alternative yielded substantial inventory savings. For the same problem faced by Hewlett-Packard, Lee and Billington (1993, 1995) developed a more detailed version of their model named worldwide inventory network optimiser (WINO) that was applicable to high-volume products for which immediate availability was essential to the customers (make-to-stock products). WINO relied on the following inputs: (1) operation characteristics, such as specification of the network structure, operations performed at each node in the network, the bill of materials, the review period for each Stock Keeping Unit (SKU), transportation times between nodes (means and variances), and desired service target or inventory levels at a node for each SKU; (2) supply characteristics, such as supplier lead times (means and variances), supplier delivery performance, and supplier quality (percent acceptable); (3) process characteristics, such as production cycle and flow times (mean and variances), production capacity, downtime characteristics, and yield; and (4) demand characteristics, such as the mean and variance of demand for each final product. Moreover, WINO produced a variety of outputs: (1) inventory in different forms (raw materials, intermediate products, and final products), for different functions (as safety stock, cycle stock, and in transit), and in different locations; and (2) customer service in terms of immediate fill rate and response times. Newhart et al. (1993) worked with Bethlehem Steel Corporation in order to design an optimal supply chain using an approach that had two phases: (1) a mathematical programming formulation and heuristic solution approach to minimise the distinct number of product types held at various points in the supply chain; and (2) a spreadsheet inventory model to estimate the safety stock needed to absorb random fluctuations in both demand and lead time throughout the system. The model's function was to estimate the amounts and dollar value of inventory throughout four alternative supply chains designed to provide superior customer service to meet the final product demands of painted and unpainted coils. Arntzen et al. (1995) worked with Digital Equipment Corporation for designing a global supply chain model (GSCM).

Their MILP model aimed to minimise variable production costs, inventory costs, shipping costs, fixed production and production 'style' costs, minus the savings from duty drawbacks and duty relieves. The objective function contained also production time and transportation time terms, weighted by a factor (1-a) while the cost terms were weighted by a. These terms were used to model the effects of the "time-to-market" characteristics of the supply chain. Demand satisfaction, balance of materials, global Bill of Materials (BOM), capacity of facilities, system configuration constraints, offset trade and local content, duty drawback restrictions, and bounds on decision variables were included in the set of constraints. The model defined: (1) the number and location of distribution centres; (2) the customer distribution centre assignment; (3) the number of echelons; and (4) the product plant assignment. Camm et al. (1997) worked with Procter & Gamble and developed a MILP model in order to determine the optimal location of distribution centres and the assignment of these distribution centres to customers. The objective function of the model minimised the total cost for the previous two decisions subject to constraints expressing policy regarding distribution centre operation and assignment. The authors used a decomposition approach in order to divide the SCN model into: (1) an uncapacitated distribution centre location model; and (2) a transportation model that was integrated with a GIS. Rao et al. (2000) worked with Caterpillar in order to optimise the design of a new product line SC by using decomposition techniques, network optimisation theory, inventory modelling, and simulation theory. This SC design model incorporated capacity constraints, lead times, and multiechelon safety stock costs for multiple items. To account for inventory safety stock costs under uncertain demand, the authors decomposed the problem into a separate network routing problem and a stochastic inventory problem. The design concerned the determination of which dealers would be served by which distribution points for each product, which was determined through the network routing model. The network routing problem was formulated as a standard minimum-cost network flow problem, which was then converted to an equivalent problem of finding the shortest path from each source to each dealer for every product. Each dealer was then assigned to its least-cost distribution point for every product. In addition to determining the least-cost distribution point for each dealer–product combination, the network routing model also determined the shortest lead-time source, which was used for expedited deliveries in the case of product shortages.

2.2.3 The penetration of SCN modelling in industries

Parallel to models, developed in order to tackle specific problems and to support SCN decision making in individual companies, a branch of SCN modelling literature focus on a more broaden area by considering features of specific industries. In this direction, Gunnarsson et al. (2004) developed an optimisation model describing the planning problem for a supplying company in the forestry industry. The MILP model aimed to minimise the total cost for satisfying a contracted demand subject to forwarding, flow balancing, capacity, and demand satisfaction constraints. Although the resulting model became very large the authors used a heuristic approach based on sequential LP solving or the direct use of commercial Integer Programming (IP) and solve the problem within practical time limits. The suggested model along with the solution approach developed with the scope to be used as a support tool for both tactical and strategic decisions in the considered industry.

Neiro and Pinto (2004) presented a framework for modelling petroleum SCs. They proposed a large-scale MINLP model, in which the structure of the network is created by connecting three basic models: (1) processing unit model; (2) tank model; and (3) pipeline model. The objective function aimed at maximising the revenue obtained by the product sales minus costs related to raw material, operation, inventory and transportation. The authors illustrated the proposed model by modelling a simplified supply chain network of a petroleum company having four refineries. Al-Othman et al. (2008) studied the same industry and proposed two formulations in order to deal with the optimal planning of a petroleum SCN. The authors proposed two LP mathematical formulations, one deterministic and one stochastic. The first model aimed at optimising the resources by minimising the total production and logistics costs as well as lost demand and backlog penalties subject to material balances, demand balances, production and storage capacities. A sensitivity analysis was performed in this model showing that planning in an uncertain economic environment is risky. The second model had the same objective function but some modifications were made in order to incorporate uncertainty. The two models were implemented in a realistic hypothetical case study and they were compared having Expected Value of Perfect Information (EVPI) as a criterion. The second model proved to be more effective as its EVPI was lower and also uncertainty in market demand has more impact on the SC plan than the actual market prices.

Guillén et al. (2006b) focused on the strategic level of the chemical SCN design problem under demand uncertainty. Their model involved the identification of the combination of suppliers, producers, and distributors able to provide the right mix and quantity of products and services to customers in an efficient way depicted by the total expected profit. The authors in order to tackle the aforementioned problem, proposed a rigorous multistage stochastic mathematical formulation and a decomposition strategy aiming at overcoming the numerical difficulties associated with the resolution of the underlying large-scale MILP model. For the same industry, Guillén and Grossmann (2009) studied the design of sustainable chemical SCs in the presence of uncertainty in the life cycle inventory associated with the network operation. They formulate a bi-criterion stochastic MINLP model that accounts for the maximisation of the Net Present Value (NPV) minimisation of the environmental impact for a given probability level with constraints in mass balances and capacities. The MINLP model was further reformulated as a parametric MINLP model and was solved by decomposing it into two problems and iterating between them. The solutions obtained by the proposed model and solution method provided valuable insights into the chemical SC design problem. The plant process industry concern Corsano and Montagna (2011) as they proposed a MILP model for the simultaneous optimisation of SCN and multiproduct bath plant design. The model aimed at minimising of the total annual cost consisted of installation, investment, production, operating, and logistics cost taking into account and assessing the tradeoffs between plants and supply chain decisions. Several numerical examples were used in order to test model's applicability and the results highlight the benefits of this integrated approach compared to a sequential counterpart.

Sousa et al. (2008) focused on pharmaceutical and agrochemical supply chains characterised by a large portfolio of products and an extensively wide distributed manufacturing network over long time periods. They propose a two stage MILP model for the optimal redesign and distribution network assessment so as to provide a template plan for the company's annual activity cycle that sets feasible objectives at the scheduling level without reducing production and sales volume and keeping inventory at the possible minimum levels. The outputs of the first stage were: (1) location of manufacturing and storage facilities; (2) allocation of production and customers; and (3) product campaign map and stock profiles. These outputs were used as input parameters to the second stage which concerned a detailed production and distribution plan. The objective function of the first stage model was the NPV maximisation while that of the second stage model was the maximisation of the net profit along with a penalty term for delays in fulfilling orders. The production, distribution, and capacity planning of a global supply chain from the process industry, and more specifically from the agrochemical industry, was addressed by Liu and Papageorgiou (2013). The authors introduced a multi-objective (moMILP) with total cost, total flow time and lost sales as key objectives and adapted two solution approaches, namely, the e-constraint method and the lexicographic minimax method, in order to construct the Pareto efficient curve and further to obtain a fair solution among optimal SCN configurations.

The automotive industry stimulate the research attention of Bihlmaier et al. (2009) and they presented a two stage stochastic MIP strategic network design problem under uncertain demands from a capacity and production planning perspective. The objective of the model was to determine the production and transportation potentials as well as the shortfalls by minimum costs and under a given corporate strategy and policy. Customised solution approaches, based on Bender's decomposition, were implemented and validate the applicability and the computational efficiency of the model. For the same industry, Kauder and Meyr (2009) addressed the strategic network planning for international manufacturers of premium cars. Two MIP formulations were developed with the first considering investment planning and supply chain planning whereas the second considering process flexibility along with the two precious aspects. Both models returned optimal solutions for small problem instances at reasonable time but when a special set of constraints, so-called "chaining constraints", was included, in order to integrate the two MIP formulations, the computational effort was worsened significantly.

The battery recycling industry, closely related to automotive industry, was investigated by Sasikumar and Haq (2011) who introduced a multi-echelon, multi-product, closed loop distribution supply chain network model that integrated the selection process of best third-party reverse logistics provider (3PRLP) to achieve cost efficiency and delivery schedules in reverse logistics. The resulting cost minimisation

MILP model along with the fuzzy VIKOR multi-criteria decision making methodology, for the selection of 3PRLP, was validated on the operations of a battery manufacturer and substantial cost saving were documented in comparison to a forward supply chain. Kannan et al. (2010) engaged with the same industry and developed an integrated multi-echelon, multi-product MILP model to optimise the distribution and inventory level for a closed loop SCN using a genetic algorithm in the context of a lead acid battery production. The total cost minimisation was the objective of the model and a heuristics based genetic algorithm was introduced in order to solve the model. The proposed heuristic performed very well in terms of quality of solutions and computational time and in larger size real world problems outperformed the solvers of the commercial software GAMS. Moreover, a cost reduction of 32.4% had been achieved by integrating forward SC with the reverse SC.

Vila et al. (2009) focused on the forestry industry and proposed a methodology to capture the dyadic relationship between a lumber company production-distribution network and its market opportunities in order to increase profitability. The developed two stage stochastic MIP was solved with a sample average approximation method based on Monte Carlo sampling technique. The first stage decision variables were constrained mainly by supply, capacity deployment and flow equilibrium relationships, whereas the second stage decision variables were constrained mainly by capacity, flow equilibrium and demand constraints. Hasani et al. (2012) proposed a robust closed-loop SCN design model for the food and high tech-electronics industries, where the properties of products, such as price and warehousing lifetime period, are time dependent. The proposed robust optimisation model, based on computational results, prove to be capable of dealing with inherent uncertainties without requiring extensive historical data. Fenies et al. (2010) considered the franchised bakery industry and proposed a modelling process composed of two modelling processes: a first modelling based on simulation/optimisation and a second modelling based on a MILP model that used data given by the first model. The second MILP model aimed to find an optimal design of the SCN for the franchisor in terms of a choice between company-owned and franchised outlets. Cintron et al. (2010) considered the consumer goods industry and developed a MILP model with an aim to design the best possible SC distribution network. The model considered multiple objectives namely: profit, lead time, power, customer’s credit performance, and distributor’s reputation. The model was validated with real data from a consumer goods company to show its functionality and also multiple runs were made in order to account for variability in demand. Syam and Côté (2010) proposed a facility location-allocation model for services industry with an application to non profit health care organizations. The proposed multi-objective MIP model aimed at finding the optimal location of facilities based on the cost of providing care and the level and extent of the care provided. Costa et al. (2011) presented a two-level network design model with intermediate facilities applied in the context of electrical distribution networks. The model was formulated as a MINLP problem with a large number of integer variables. A hybrid exact–heuristic approach was proposed by the authors in order to solve this NP-complete model.

Almansoori and Shah (2006) developed a MILP SCN design model for the hydrogen energy industry with aim to minimise both capital and operating costs within the SCN that will satisfy hydrogen demand for vehicular use in Great Britain. For the same industry, Kim and Moon (Kim & Moon, 2008) introduced a generic moMILP SCN design model under demand uncertainty. Cost efficiency and safety where the two objective functions directions and the results of model's implementation into the future hydrogen SC of Korea revealed feasible optimal network configurations.

The most recent and popular industry, in which SCN modelling community has steer its interest to, is the bioenergy industry. There is a sound number of works that focus on biofuel SCN's with the aim to optimise their design and operation. On these lines, Ekşioğlu et al. (2009) proposed a mathematical model capable of designing and managing a biomass-to-biorefinery supply chain and by using a case study they show model's ability to identify potential location for biorefineries and to give insights about the factors that impact the delivery cost of c-ethanol. Dal-Mas et al (2011) introduced a time dynamic MILP SCN design model for biofuels systems, which incorporated different features of spatially explicit location of networks nodes and capacity planning, applied in the emerging Italian corn-based ethanol production while Giarola et al. (2011) developed an analogous spatially explicit moMILP model to design hybrid first and second generation bioethanol SCNs. Kim et al. (2011) extended their previous work (Kim, Realff, Lee, Whittaker, & Furtner, 2011) and considered an analogous MILP biofuel SCN design model with a focus on robustness analysis and Monte Carlo global sensitivity analysis on five dominant parameters, namely, biomass availability, maximum demands, sale price of each final product, yield of interest product, and yield of final product. Akgul et al. (2012b) enriched their previous single objective model (Akgul, Shah, & Papageorgiou, 2012a) with a moMILP for a hybrid first/second generation biofuel SCN design model that considered economic and environmental objectives simultaneously.

2.2.4 Current and emerging SCN modelling issues

In the light of the 21st century, SCN modelling is considered a hot research area that provides to companies several decision support models capable of capturing, handling, and managing most of the quantitative and qualitative features that arise within the business environment that a SCN operates. Decision makers need for sophisticated and integrated models has forced the OR/MS community to deepen and widen its studies in the field.

On these lines, models featuring cost minimisation and profit maximisation objective functions have gradually been accompanied by other objective functions and had been forming multi-objective models. Sabri and Beamon (2000) contributed to this research stream by developing a four-echelon, multi-objective SCN design model consisted of a conceptual framework, a mathematical formulation, and a solution algorithm aiming to aid decision makers in the: (a) design of efficient, effective, and flexible SCN's and (b) evaluation of competing SCN's. Altiparmak et al. (2006) introduced a new solution procedure, based on genetic algorithms, to find the set of

Pareto-optimal solutions for multi-objective SCN design problems. The model was formulated as MINLP and its applicability was illustrated through a case study from a plastic producer in Turkey. Minimising total cost, maximising robustness to various scenarios, maximising the local incentives, and minimising the total transport time were the four objectives of the MINLP SCN design/planning model proposed by Chen et al. (2007). Maximisation of profit and quality, in terms of suppliers defect raw materials minimisation, were the two objectives of the stochastic optimisation model developed by Franca et al. (2010) while minimisation of the total SCN cost along with maximisation of the total compatibility index in strategic alliance were the objective functions of a stochastic multi-objective optimisation SCN configuration model proposed by Nepal et al. (2011). In this model the novelty lied in the three constituents formulating the compatibility index, namely, structural (cultural alignment, communications and information sharing, coordination, and cooperation), managerial (managerial trust and commitment, compatibility in strategic goals, and conflict management techniques), and financial (profit margin, return on investment, and bond rating). The model was converted into a weighted goal programming model and a heuristic genetic algorithm approach was used in order to solve the example bulldozer case study. Selim and Ozkarahan (2008) presented a multi-objective LP model to address the SCN design problem by using a fuzzy modelling approach. The goal of the model was to select the optimum numbers, locations and capacity levels of plants and warehouses to deliver the products to the retailers at the least cost while satisfying the desired service level. Recently, You and Grossmann (2011) formulated a bi-criterion MINLP SCN design model with the objectives of minimising annualised cost and minimising the minimum guaranteed service times of the markets. The model was applied in an acetic acid SCN and the results supported its implementation in multi-echelon inventory systems. Wang et al. (2011) provided a multi-objective MIP formulation for the SCN design problem that considered the environmental investment decision and consisted of minimising total cost and environmental influence. Authors applied a normalised constraint method in order to find a set of even distributed Pareto optimal solutions and conducted a comprehensive set of numerical studies to test model's sensitivity to various parameters. Results indicated that improving the network's capacity and increasing the supply to facilities can decrease CO_2 emission of the whole SCN and also the total cost.

Cost savings, environmental requirements, social responsibility, and governmental legislation are the main pressures to the thriving research branch of reverse flow and closed-loop SCN modelling. A plethora of models exist in the relevant literature and each of which contributes to the field by one or more novel features. In specific, Min et al. (2006) proposed and tested a cost minimisation MINLP model and a genetic algorithm capable of solving the reverse logistics problem involving both spatial and temporal consolidation of returned products. Inspired by the practice of original equipment manufacturers in the automotive industry, where service parts are provided for vehicle maintenance and repair, Üster et al. (2007) considered a cost minimisation large scale MILP closed-loop SCN design model along with a Benders decomposition approach, with multiple cuts, for efficiently solving. A stochastic

MINLP dynamic reverse logistics network was introduced by Lee and Dong (2009) that considered uncertainties in demand of forward products and in supply of returned products. A solution method which integrated sample average approximation with a simulated annealing developed by the authors and in various numerical experiments proven to yield efficient solutions.

Salema and colleagues contributed substantially in the closed loop SCs by introducing, among others, three distinct models. The first MILP model extended a recovery network model by addressing its drawbacks in unlimited capacity, single product, and lack of uncertainty handling. The proposed model was evaluated in an Iberian company with the results indicating it applicability in medium size problems (Salema, Barbosa-Povoa, & Novais, 2007). Their second model was differentiated in the simultaneously accounting of strategic and tactical decisions. Strategic decisions concerned the network's configuration whereas tactical concerned production, storage and distribution planning. A two time scale, involving a macro time and a micro time, served to interconnect strategic decision with tactical (Salema, Barbosa-Povoa, & Novais, 2009). Their third MILP model generalised the previous ones by allowing the network's entities and constraints to not directly linked with the real entities (such as factories, warehouses, and so on) but as capacitated transformation points (Salema, Barbosa-Povoa, & Novais, 2010). El-Sayed (2010) proposed a multi-period, multi-echelon, forward-reverse stochastic MILP model that aimed to optimise the design of a logistics network. The total expected profit was the model's objective function while the network's topology, production rates, transportation flows, and inventory levels were its main decision variables. The model was verified by using a small size example and proved reliable although its application is limited to single item, single product problems.

In the same research branch, a multi-objective possibilistic MILP closed-loop SCN design model under uncertainty was introduced by Pishvaee and Torabi (2010) where its main abilities were summarised into : (1) integration of forward and reverse flows, (2) support of both recovery and recycling processes, (3) consideration of second kind customers (e.g. customers of recycled material), (4) trade-offs allowance between total costs and total network responsiveness, and (5) handling of different environmental and system uncertainties. Latterly, the Pishvaee et al. (2011) developed a similar single objective MILP model that was focused on explicitly handling the inherent uncertainty of input data in a closed-loop SCN. Computational experiment shown that the proposed robust model is superior to its deterministic counterpart in both handling the uncertainty and the robustness of respective solutions. Other recent works are those of: (1) Özkır and Başlıgıl (2012) where they introduced a MILP model to obtain the optimal closed-loop SCN configuration, in which recovery process occurred in three different ways: material recovery, component recovery, and product recovery; (2) Lieckens and Vandaele (2012) where they developed an advanced strategic planning model for the design of complex closed-loop SCs with multiple levels and a high degree of uncertainty by integrating queueing relationships that measure the impact of delays and inventory levels; (3) Abdallah et al. (2012) where they integrate location and inventory decisions between the forward and reverse SC within an

MINLP model that was solved and analysed through parameter sensitivity; and (4) Alumur et al. (2012) where their multi-period reverse logistics MILP model accommodated modular capacities, capacity expansion, reverse bill of materials, minimum throughput, variable operational costs, finite demands in secondary market, and a profit oriented objective function.

Another current research area in SCN modelling is that of sustainable, environmental, and green SCNs where the direction of researchers' endeavours is to formulate and manage issues like life cycle assessment (LCA), industrial ecology, environmental engineering, carbon footprint, and green house gases emissions, among others. In this framework, Hugo and Pistikopoulos (2005) presented a moMILP SCN design model, along with a solution algorithm, with an emphasis on the use of an impact assessment method within the quantitative LCA framework and on the economies of scale that dictate capital investment decisions whereas Bojarski et al. (2009) introduced a similar multi-period moMILP SCN design and planning model with a specialisation on environmental impact, such as direct emissions, purchased energy emissions, raw materials production emissions, and transportation distribution emissions, and with a modelling approach for LCA concepts. Other recent sustainable SCN design models are those of: (1) Chaabane et al. (2012) with a focus on LCA methodology, greenhouse gases emissions, and targets for recycling products at their end of their life; (2) Elhedhli and Merrick (2012) with a focus on relating vehicle weight to CO_2 emissions; and (3) Mallidis et al. (2012) with a focus on particulate matters (PM) and CO_2 emissions.

For many years, inventory theory aspects had been examined in isolation from other operations in multi-echelon SCNs and many single-product, single-echelon, single-period models existed in the literature. However, as these issues are vital in current SCNs, researchers fulfil this need by introducing appropriate decision support models. Scilicet, Miranda and Garrido (2004) introduced a MINLP SCN design and planning model, coupled with a heuristic solution approach based on Lagrangian relaxation and the sub-gradient method, which considered economic order quantity and safety stock decisions. A very similar, in formulation and optimisation procedure, model proposed by Nasiri et al. (2004) and the results of their extensive computational tests indicated the effectiveness and the efficiency of their model in a wide variety of problem sizes and structures. Recently, Park et al. (2010) formulated a MINLP SCN design model where risk-pooling strategy is incorporated and lead times are depended on distribution centre-to-supplier pairs. The derived two-phase heuristic solution algorithm, based on Lagrangian relaxation and the sub-gradient method, proved efficient and effective according to experimental results.

Other current and emerging aspects in SCN modelling literature are: (1) vehicle routing modelling (see contributions by Lashine et al. (2006), Lee et al. (2009), and Ahmadi Javid, and Azad (2010)); (2) quality modelling (see contributions by Das and Sengupta (2010) and Castillo-Villar et al. (2012)); (3) robustness modelling (see contributions by Meepetchdee and Shah (2007) and Shukla et al. (2011)); and (4) supplier selection modelling (see contribution by Cakravastia et al. (2002)).

2.3 SCN modelling with uncertainty

Manufacturing industry companies operate a wide variety of assets, with widely varying ages and expected lifetimes. At any given time, the decisions relating to investment in infrastructure include how best to configure assets at existing sites and whether to establish new sites. These are tied in with production and inventory planning. The main issue associated with investment planning is that capacity-related decisions have impacts far beyond the time period over which confidence in data exists. Hence, decisions must be made in the face of significant uncertainty relating in particular to the economic circumstances that will prevail in the future. Uncertainty may be caused by external factors, such as demand, prices, availability of production resources etc. or internal ones like promotion of new products, improvement of product quality etc. Demand uncertainty has been early recognised in the supply chain management context as the essential cause of the ‘bullwhip effect’, which is characterised by excess volatility in demand (Davis, 1993). This phenomenon, which in its early existence was called demand amplification, has been an issue that continues to concern companies as some studies reported a 20:1 amplification from end-to-end in various SCs (Geary, Disney, & Towill, 2006).

Systematic consideration of uncertainty can facilitate calculation of expected return and evaluation of associated risks based on current status and future predictions (Papageorgiou, 2009). Applequist et al. (2000) presented an approach for the design of chemical SCs under demand uncertainty. They mentioned that in such cases, risk appears and management issues become more complex and difficult. Gupta et al. (2000) presented a mathematical programming framework for the mid-term SC planning under demand uncertainty. Issues relevant to customer demand satisfaction and inventory management were considered in details. Results illustrated that significant improvement in customer services levels can be achieved with a small charge in total cost. This work was then extended by Gupta and Maranas (2003), who modeled the manufacturing decisions as ‘here-and-now’ decisions and the logistics ones as “wait-and-see decisions”. Tsiakis et al. (2001) show how demand uncertainty can be introduced in a multiperiod steady-state model. They argue that future uncertainties can be captured well through a scenario tree, where each scenario represents a different discrete future outcome. These should correspond to significant future events rather than just minor variations in demand. They utilise a multipurpose production model where flexible production capacity is to be allocated between different products, and determine the optimal layout and flow allocations of the distribution network. Alonso-Ayuso et al. (2003) introduced a two-stage stochastic 0-1 modelling and a related algorithmic approach aiming to formulate strategic and tactical supply chain decisions under uncertainty. The objective was the maximisation of the product net profit over the time horizon minus the investment depreciation and operations costs. The pharmaceuticals SCs constitute an interesting area in which significant discrete uncertainty exist (related to success or failure of product tests and clinical trials). The problem of testing and capacity planning in this sector has been reviewed by Shah (2004). Chen and Lee (2004) presented a MINLP problem for the design and operation of SC under multiple objectives and uncertain product demand. Santoso et al. (2005) proposed a stochastic programming model and a solution algorithm to solve large-scale global supply chain network design problems under uncertainty and with an extremely large number of scenarios. Uncertainty was captured in terms of randomness in costs, capacities, supplies and demands. The objective was the minimisation of the total investment and operational costs. Guillén et al. (2005) proposed a multi-echelon stochastic model for the design of chemical SCs under demand uncertainty. A clever combination of genetic algorithms and mathematical programming was employed for the solution of the underlying problems. Hua et al. (2006) illustrated how coordination between manufacturers and retailers can improve competitive advantage in SCNs. Two situations with different market conditions were examined. In the first case, wholesale prices and orders size were decisions, whereas in the second case retailer prices were also taken into account. It was concluded that an efficient coordination mechanism can benefit SCs. Al-Othman et al. (2008) presented a multi-period optimisation model framework for the optimal design of petroleum SCs under uncertainty in both product demands and prices. They concluded that the design of supply chains in such uncertain and unstable economic environments is characterised by high levels of danger and risk, since many unpredictable factors can be appeared. You and Grossmann (2008) presented a mixed-integer optimisation approach for the optimal design of responsive supply chains in the present of demand uncertainty. A multi-period MINLP model was developed for the maximisation of net present value and minimisation of expected lead time. Mitra et al. (2008) developed a chance constrained programming approach to consider uncertainty issues in the multisite multiproduct SC planning problem. Amaro and Barbosa-Póvoa (2009) proposed a multi-period model for the planning of closed loop SCs under demand uncertainty. The formulation considered operational, economical and markets aspects simultaneously and its novel features were the concepts of reverse logistics concerns and partners relations. The applicability of the model was illustrated in a pharmaceutical SC and further improvements were mentioned. You and Grossmann (2010) presented a MINLP model that determined the optimal network structure, transportation, and inventory levels of multi-echelon SC under customer demand uncertainty. The initial MINLP model was reformulated as a separable concave minimisation program and a spatial decomposition algorithm was introduced in order to obtain near global optimal solutions. The applicability of the model was illustrated via two SC examples and the results were discussed an analysed. Pan and Nagi (2010) considered the design of a SC for a new market opportunity with uncertain customer demands. A robust optimisation model was proposed where expected total costs, cost variability due to demand uncertainty, and expected penalty for demand unmet were the three components in the objective function. In this model uncertainty was captured via scenario approach while the objective was to choose one partner for each echelon and simultaneously decide for each partner the production plan, inventory level, and backorder amount. Mohammadi Bidhandi and Mohd Yusuff (2011) extended their previous deterministic work (Mohammadi Bidhandi, Mohd. Yusuff, Megat Ahmad, & Abu Bakar, 2009) and developed an integrated, multi-commodity, single-period SCND model under uncertainty and a solution method that combined Bender's decomposition approach and sample average approximation technique. Under various computational experiments, on a set of randomly generated test problems, the results proved that the proposed method solves efficiently SCND problems.

SCN modelling under uncertainty have received significant attention in the literature. The body of literature related to these models is extensive. A comprehensive review of all models available or used in the design and operation of SCNs is not possible within the confines of a single chapter. Interested readers could refer to the excellent reviews of: (1) Snyder (2006) regarding approaches for optimisation under uncertainty applied in facility location problems; (2) Gümüs and Güneri (2007) about multiechelon inventory management in SCNs with uncertain demand and lead times; (3) Papageorgiou (2009) regarding systematic consideration of uncertainty within SCN optimisation problems for the process industries; (4) Peidro et al. (2009) for a comprehensive taxonomy of quantitative-based approaches for SCN planning under uncertainty, e) Klibi et al. (2010) regarding SCND problems under uncertainty and the available models proposed to support the design process.

2.4 SCN modelling with financial considerations

Despite the fact that many researchers have mentioned the importance of financial considerations in the SCNM context (Hammami et al., 2008; Melo et al., 2009; Papageorgiou, 2009; Shapiro, 2004) very few research contributions can be found in the literature. SCNM models with financial aspects could be divided into two groups. Those where financial aspects are considered as endogenous variables which model the financial operation and are optimised along with the other SCN variables and those where financial aspects are considered as known parameters used in constraints and in the objective function.

Regarding the first group, Romero et al. (2003) build a deterministic multi-period mathematical model for the batch chemical process industry that combined scheduling and planning with cash flow and budget management. In the same vein, Badell et al. (2004) proposed an unequal multi-period deterministic MILP model for the batch process industries that integrates advanced planning and scheduling at plant level with cash flow and budgeting. Yi and Reklaitis (2004) presented a two level parametric optimisation model at plant level for the optimal design of batch storage networks that integrated production decisions with financial transactions through cash flow assignment in each production activity. Guillén et al. (2006a; 2007) introduced a deterministic MILP model, for a multiproduct, multi-echelon chemical supply chain, which optimises planning/scheduling and cash flow/budgeting decisions simultaneously. The model is multi-period and its objective function is the change in company's equity, a novel feature against previous models. Laínez et al. (2007) proposed a deterministic MILP model for the optimal design of a chemical SC based on holistic models that covered both the process operations and the finances of the company and aimed at maximising the corporate value of the firm. Recently, Puigjaner and Guillén (2008b) developed a holistic agent-based system that was able to use a number of different tools such as if-then analysis rules and mathematical programming algorithms in order to capture all processes in a batch chemical SC. A budgeting model was among these features and its connection to the agent-based system was made through payments of raw materials, production and transport utilities, and the sale of products. A deterministic comprehensive SCN redesign model that incorporated capital budgeting and asset management was proposed by Naraharisetti et al. (2008). Management of loans and bonds for raising capital was the main financial aspect novelty of this MILP model. Nickel et al. (2012) considered a multi-period multi-commodity stochastic SCND problem with financial decisions and risk management. The proposed MILP model aimed at maximising the total financial benefit of the SCN and incorporated uncertainty in demand and interest rates.

Regarding the second group, Canel and Khumawala (1997) provided an efficient branch and bound procedure for solving the uncapacitated multi-period international facilities location problem. Financial incentives, exchange rates, taxes and tariffs were the financial parameters incorporated in their 0-1 Mixed Integer Problem that aimed to determine: (1) in which countries to locate manufacturing facilities; (2) quantities to be produced at these facilities; and (3) the quantities to be shipped from manufacturing facilities to the customers. A budget constrained dynamic, multiple objective, MILP model was proposed by Melachrinoudis and Min (2000). The model aimed to determine the optimal timing of relocation and phase-out in a multiple planning horizon. In a similar vein, Wang et al. (2003) introduced a budget constrained location problem in which the opening of new facilities and closing of existing facilities was considered simultaneously. The objective was to minimise the total weighted travel distance for customers and due to the model's NP-hardness the authors developed three heuristic algorithms to solve the problem. Avittathur et al. (2005) presented a model for determining the optimal locations of distribution centres based on trade-offs between central sales tax structure and logistics efficiency in the Indian context. The model was initially formulated as a MINLP problem and then it was approximated to a MIP problem. Simulation experiments showed that the central sales tax rate is an important driver of the optimal number of distribution centres required. Melo et al. (2006) presented a dynamic multi-commodity capacitated facility location model. The model was formulated as a mixed integer linear programming problem that consider simultaneously many practical aspects of SCND such as external supply of materials, inventory opportunities for goods, distribution of commodities, storage limitations and availability of capital investments which was the financial aspect incorporated in the model. In each time period, there was a limited amount of capital for capacity transfers, for shutting down existing facilities and/or for setting up new facilities. This amount was given by a budget initially available as a parameter. Tsiakis and Papageorgiou (2008) presented a deterministic MILP model for the optimal configuration of a production and distribution network. The objective was to minimise the total cost across the network and financial constraints for exchange rates and duties were incorporated in the model. Hammami et al. (2009) proposed a SCND model that integrated all the relevant components that characterise the delocalization problems, as identified in Hammami et al. (2008). The model was multi-product, multi-plant, and multi-echelon and was formulated as a MILP. Financial aspects in this model were transfer pricing, allocation of suppliers' costs and transportation cost allocation. Sodhi and Tang (2009) presented a stochastic linear programming SC planning model similar to the asset-liability management model. Cash flow management and borrowing constraints were the financial aspects of the model which aimed at maximising the expected present value of the net cash in a given planning horizon.

2.5 Conclusions

Because of its widespread application and significant strategy impact, SCN modelling has received a semantic amount of attention in the research literature. The body of literature in this area is vast and is flourishing astoundingly hitherto. The above literature review aimed at providing as many as possible works in the area but in line with the scope of the Thesis. In this sense, the literature is fragmented to OR perspective and more specific to analytical models as the development of such models are the main objective of the present Thesis. However, various non-analytical models have been presented in order to gain a wider view of the research in the field.

Judging from the literature, research on integrated SCN design models that capture financial aspects and matters is still in its infancy. However, as SCN managers require holistic decision support models that track and quantify the financial impact of their production and distribution decisions, this research stream is likely to become a mainstream. To fill this research void, this Thesis aims to enrich the relevant literature by providing several SCN design models that incorporate financial issues and assist SCN managers in strategic decision making.

CHAPTER 3

Optimal design of SCNs under uncertain transient demand variations

3.1 Introduction

The operation of a SCN does not normally occur at a steady state. Usually product demands vary with time as a result of fluctuations in consumption patterns and product life cycles. For this reason, companies are forced to predict demand variation and to be prepared to face possible increases or decreases.

Steady state models are a justified approximation of the operation of SCNs when we are not interested in long-term variability. This is because short-term fluctuations are captured implicitly, to a certain extent, by averaging the material flows in the network over a sufficiently long period of time. On the other hand, modelling of long-term variations, such as systematic variation of demand with time (e.g. seasonality or growing declining markets), necessitates a time dependent approach.

In this chapter a detailed and dynamic model for the problem of designing SCNs, comprising multiproduct production facilities with shared production resources, warehouses, distribution centres and customer zones, in which demands of products are both uncertain and time-varying, is proposed. Inventories can be kept in different nodes of the network over several time periods, whereas uncertainty is expressed with a scenario approach. The objective is the minimisation of total annualised expected cost of the network by considering all structural and operating constraints.

Section 3.2 introduces the approach according to which demand uncertainty is tackled followed by a mathematical programming formulation in Section 3.3. The applicability of the developed model is illustrated in Section 3.4 by using a large-scale case study, under different levels of safety stocks. Finally, concluding remarks are drawn in Section 3.5 by commenting and communicating the case study results.

3.2 Representation of uncertainty

Due to the long planning horizon intrinsic in SCN design problems a high level of uncertainty is often encountered. The handling of this uncertainty raises many challenges from the choice of an appropriate modelling method to the solution method selected to attack the problem (Wets, 1996). In the case of SCNs as in any production and distribution system we are mainly interested in the uncertainty in product demands, prices, costs and availability of resources. Dynamic mathematical formulations approach uncertainty in two ways (Ierapetritou, Pistikopoulos, & Floudas, 1996):

I. scenario or multi period approaches often including discretisation applied to a continuous uncertain parameter space; and
II. probabilistic approaches using two stage stochastic programming.

In the two-stage stochastic programming approach, the decision variables of a model under uncertainty are partitioned into two sets. The first stage variables are those that have to be decided before the actual realization of the uncertain parameters. A recourse decision can then be made in the second-stage that compensates for any bad effects that might have been experienced as a result of the realization of uncertain parameters. The optimal policy from such a model is a single first-stage policy and a collection of recourse decisions (a decision rule) defining which second-stage action should be taken in response to each random outcome. The objective is to choose the first-stage variables in a way that the sum of the first-stage costs and the expected value of the random second-stage costs is minimised. The concept of recourse has been applied to linear, integer, and non linear programming. In a stochastic SC design framework the binary variables can be treated as first-stage variables denoting, for example the selection of distribution centre or warehouses, whereas the continuous variables (e.g. transportation rates, production rates) can serve as a resource in the second stage problem to adapt to uncertain parameter realization. The overall concepts been applied to a wide range of problems (Li & Ierapetritou, 2008; Sahinidis, 2004).

The scenario-based approach divides the planning horizon into a number of stages. The boundaries between successive stages reflect points in time where important uncertainties will be resolved. These often relate to important external events (economic or geopolitical etc.) or important internal events (launches of new products, patent losses on existing products etc.). Normally, the number of scenarios is kept small, the aim being to capture only the most important events. Schoemaker (1993) explained how to construct scenarios, Schnaars (1987) made a comparative evaluation of the many techniques that had been proffered to generate scenarios, and also Bunn and Salo (1993) offered some practical guidelines on using scenarios to support strategic planning.

In the SC literature uncertainty in time varying demands has received attention in the context of the planning and control of inventories in multi-echelon networks. Some of the mathematical programming models tend to require substantial amounts of data and to make many restrictive assumptions which renders them impractical to some extent (Stenger, 1996). On the other hand, heuristic models fail to consider the interactions between echelons and frequently result in excessive inventories.

The scenario approach to modelling of uncertainty is particularly well suited to problems involving a combination of "wait-and-see" and "here-and-now" decisions. The nature of the scenarios that need to be postulated depends on the existence of "wait-and-see" decisions. If the problem under consideration involves no such decisions, then each scenario is a distinct profile of product demand(s) over time. In this case, all decisions are of the "here-and-now" type and are determined only on the basis of information available at the initial stage.

On the other hand in problems involving a combination of "wait-and-see" and "here-and-now" decisions the postulated scenarios are typically of the form shown in Figure 3-1. Here the information pertaining to product demands in a given period becomes available at the end of the preceding period and thus resulting in each scenario branch breaking into multiple branches at these points. In many cases there is little or no uncertainty regarding the very first period and thus this results in a single scenario branch over this period as shown in Figure 3-1.

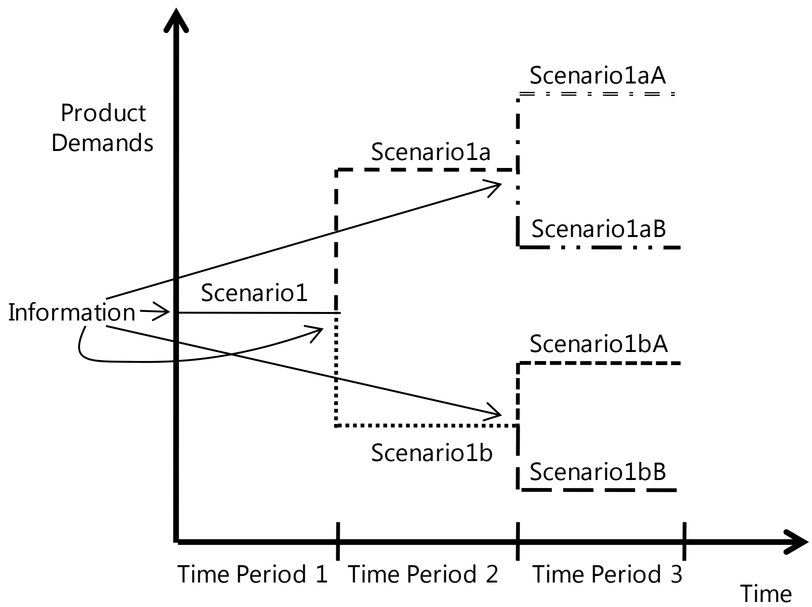


Figure 3-1: Scenarios for problems involving both "here-and-now" and "wait-and-see" decisions

In this chapter, a scenario planning approach is adopted for handling the uncertainty in time varying product demands. A question that needs to be addressed in this context concerns the generation of the scenarios to be considered. It is, of course, possible to assume that the demand for each product in each customer zone is an independent random parameter. However, more realistically, demands for similar products will tend to be correlated and will ultimately be controlled by a small number of major factors such as economic growth, political stability, competitor actions, and so on.

The overall aim should be to construct a set of scenarios representative of both optimistic and pessimistic situations within a risk analysis strategy. A 12-step procedure for generating appropriate scenarios and a discussion on the use of scenario planning techniques were presented by Vanston et al. (1977). Recently, Karuppiah et al. (2010) presented a new practical heuristic strategy for solving two-stage stochastic programming problems formulated as deterministic multi-scenario optimisation problems. The idea consists of replacing a given set of scenarios, obtained by discretisation of the uncertain parameter space, by a smaller set of scenarios and thus approximating the optimisation problem in a reduced space. A MILP is proposed for the reduced scenario selection.

From the practical point of view, the total number of scenarios that have to be considered is typically much smaller than what might be expected given the (often large) numbers of products and customer zones. In any case, for the purposes of this work, we will assume that product demand estimates (in each time period) represent both optimistic and pessimistic situations while the time varying profiles have been defined using historical trends.

There are now three important sets of decisions associated with each decision-making time period and each branch on the tree:

I. whether to invest in new capacity and if so, how much;
II. how much material to produce;
III. how much inventory to carry over to the next period.

In some decision-making models, the amounts produced over each branch are assumed to be equal to demand and thus this effectively removes the inventory decisions and the additional flexibility of action that is available to the decision maker. If maintenance strategy is important, then maintenance decisions and their effect on equipment availability would be included.

From the mathematical point of view, the scenario-based approach results in a mathematical programming optimisation problem. The complexity of the latter depends primarily on:

I. the complexity of the underlying process model; for example, non linear models are more complex than linear ones, and models involving discrete decisions (as is often the case with flexible multipurpose plants) are even more complex;
II. the number of postulated scenarios.

Depending on the model developed and the case under consideration the scenario-based approach often determines:

I. the optimal capital investment in new capacity that must be put in place by the start of each planning stage under each and every scenario;
II. the optimal operating policy (e.g. plant throughput) and sales volume throughout each planning stage of every scenario;
III. the inventory amounts that should be carried over from one stage to the next in each branch of the scenario tree;
IV. where relevant, the maintenance strategies for different items of equipment.

Note that, while the (postulated) product demand during any particular stage provides an upper bound on the (optimal) sales volume, the two are not necessarily equal. Moreover, the sales volume during a certain stage is not necessarily equal to the production rate given the possibility of inventory carry-over from earlier stages.

It should be noted that the scenario-based approach is often preferable by the industry as it can easily reflect variations in demand forecasts.

3.3 Mathematical formulation

3.3.1 Problem description

We consider a four stage network of the type shown in Figure 3-2. The locations of the plants and customers are assumed to be fixed and known. A number of ware-houses and distributions centres must be selected from a set of possible locations.

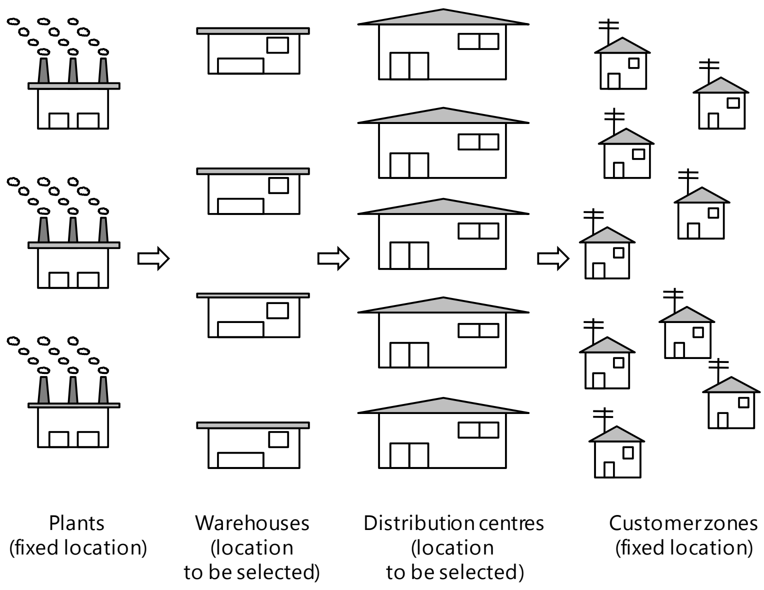


Figure 3-2: The SCN considered in this chapter

A number of sequential activities occur along this SCN and delineate its structure. Initially, the total customer base is segmented in zones through topology and marketing criteria. Demands from these zones are forecasted based on historical data. Then the SCN is configured in order to satisfy these demands.

Plants can produce any product included in company's portfolio. For each plant the production capacity and the availability of production resources is subject to certain constraints. Warehouses and distribution centres (if established) have specified maximum material handling capacities. Warehouses can be supplied from more than one production plant and can supply more than one distribution centre. In the same manner, each customer zone can be supplied from more than one distribution centre. Across the SCN costs are created due to establishment of warehouses and distribution centres, due to production and transportation of materials, and due to handling and storing of materials at warehouses and distribution centres.

The SCN decisions to be determined by the proposed model are strategic ("here-and-now"):

I. The number, location and capacity of warehouses to be set up
II. The number, location and capacity of distribution centres to be set up
III. The transportation links that need to be established in the network

and tactical ("wait-and-see"):

IV. The flows of materials in the network
V. The production rates at plants
VI. The inventory levels at each warehouse
VII. The inventory levels at each distribution centre

Our aim is to find the optimal SCN configuration that minimises the expected value of the SCN's total cost, taken over all demand scenarios and during the operation of the network, under various design and operation constraints.

3.3.2 Mathematical model (M1)

The above problem is formulated mathematically as a MILP problem (M1). Due to the importance of the binary variables we present them in this point in order to be highlighted.

$$\mathrm{PW}_m = \begin{cases} 1, \text{if warehouse } m \text{ is established} \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{PDC}_k = \begin{cases} 1, \text{if distribution centre } k \text{ is established} \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{PWDC}_{mk} = \begin{cases} 1, \text{if material is transported from warehouse } m \text{ to distribution centre } k \\ \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{PDCL}_{kl} = \begin{cases} 1, \text{if material is transported from distribution centre } k \text{ to customer zone } l \\ \\ 0, \text{otherwise} \end{cases}$$

The model is dynamic in terms of time-varying uncertain demands. Uncertainty is modelled through a scenario approach and contains both "wait-and-see" and "here-and-now" decisions, as explained in Section 3.2 and shown in Figure 3-1. Strategic decisions are "here-and-now" whereas tactical decisions are "wait-and-see".

Product demands are assumed to vary as piecewise constant functions of time defined over a number of time periods of given but not necessarily equal duration. The uncertainty in these demands is taken into account by postulating a number of scenarios $s = 1, 2, \cdots, \mathrm{NS}$, each with a potentially different set of piecewise constant demand functions. The objective is to design a SCN that can handle any one of these scenarios, which it materialise at some point during the lifetime of the SCN, so as to minimise the combined operating and capital cost of the SCN. Furthermore, inventory can be carried over from one time period to other. Failure to consider such inventory carry-over can compromise the optimality of the solution obtained by forcing each product to be produced in all periods in which a non-zero demand exists for it (Shah, 1998).

In order to arrive at a meaningful objective function for the optimisation it is assumed that the probability of scenario s occurring in practice is known and is denoted by ψ_s. These probabilities will generally satisfy the condition expressed by constraint (3.1):

$$\sum_{s=1}^{NS} \psi_s = 1 \qquad (3.1)$$

3.3.3 Nomenclature

Indices

e production resources (equipment, manpower, utilities, etc.)

i products

j plants

k possible distribution centres

l customer zones

m possible warehouses

s product demand scenario

t time period

Sets

K^{SS} set of distribution centres that should be supplied by a single warehouse

L^{SS} set of customer zones that should be supplied by a single distribution centre

Parameters

C_{im}^{WH} unit handling cost for product *i* at warehouse *m*

C_{ik}^{DH} unit handling cost for product *i* at distribution centre *k*

C_{m}^{W} annualised fixed cost of establishing warehouse at location *m*

C_{k}^{D} annualised fixed cost of establishing distribution centre at location *k*

C_{ij}^{P} unit production cost for product *i* at plant *j*

C_{ijm}^{TR} unit transportation cost of product *i* transferred from plant *j* to warehouse *m*

C_{imk}^{TR} unit transportation cost of product *i* transferred from warehouse *m* to distribution centre *k*

C_{ikl}^{TR} unit transportation cost of product *i* transferred from distribution centre *k* to customer zone *l*

C_{ijt}^{I} unit inventory cost of product *i* at plant *j* during time period *t*

C_{imt}^{I} unit inventory cost of product *i* at warehouse *m* during time period *t*

C_{ikt}^{I} unit inventory cost of product *i* at distribution centre *k* during time period *t*

D_{k}^{max} maximum capacity of distribution centre *k*

D_{k}^{min} minimum capacity of distribution centre *k*

$\mathrm{D}_{ilt}^{[s]}$ demand for product *i* from customer zone *l* during time period *t* under scenario *s*

$\mathrm{I}_{ijt}^{[s],min}$ minimum inventory of product *i* held in plant *j* at the end of time period *t* under scenario *s*

$\mathrm{I}_{imt}^{[s],min}$ minimum inventory of product *i* held in warehouse *m* at the end of time period *t* under scenario *s*

$\mathrm{I}_{ikt}^{[s],min}$ minimum inventory of product *i* held in distribution centre *k* at the end of time period *t* under scenario *s*

n^{DC} minimum inventory held at distribution centres expressed in terms of number of days equivalent of materials handled

n^{W} minimum inventory held at warehouses expressed in terms of number of days equivalent of materials handled

n^{P} minimum inventory held at production plants expressed in terms of number of days equivalent of materials handled

NS number of product demand scenarios

$\mathrm{P}_{ijt}^{[s],max}$ maximum production capacity of plant *j* for product *i* during time period *t* under scenario *s*

$\mathrm{P}_{ijt}^{[s],min}$ minimum production capacity of plant *j* for product *i* during time period *t* under scenario *s*

Q_{mk}^{min} minimum rate of flow of material that can practically and economically be transferred from warehouse *m* to distribution centre *k*

Q_{kl}^{min} minimum rate of flow of material that can practically and economically be transferred from distribution centre *k* to customer zone *l*

$\mathrm{Q}_{ijm}^{[s],max}$ maximum rate of flow of product *i* that can be transferred from plant *j* to warehouse *m* under scenario *s*

$\mathrm{Q}_{imk}^{[s],max}$ maximum rate of flow of product *i* that can be transferred from warehouse *m* to distribution centre *k* under scenario *s*

$\mathrm{Q}_{ikl}^{[s],max}$ maximum rate of flow of product *i* that can be transferred from distribution centre *k* to customer zone *l* under scenario *s*

R_{je} total rate of availability of resource *e* at plant *j*

W_{m}^{max} maximum capacity of warehouse *m*

W_{m}^{min} minimum capacity of warehouse *m*

$\Delta\mathrm{T}_{t}$ duration of time period *t*

Continuous variables

D_{k} capacity of distribution centre *k*

$\mathrm{I}_{ijt}^{[s]}$ inventory level of product *i* being held at plant *j* at the end of time period *t* under scenario *s*

$I_{imt}^{[s]}$ inventory level of product *i* being held at warehouse *m* at the end of time period *t* under scenario *s*

$I_{ikt}^{[s]}$ inventory level of product *i* being held at distribution centre *k* at the end of time period *t* under scenario *s*

$P_{ijt}^{[s]}$ production rate of product *i* in plant *j* during time period *t* under scenario *s*

$Q_{ijmt}^{[s]}$ rate of flow of product *i* transferred from plant *j* to warehouse *m* during time period *t* under scenario *s*

$Q_{imkt}^{[s]}$ rate of flow of product *i* transferred from warehouse *m* to distribution centre *k* during time period *t* under scenario *s*

$Q_{iklt}^{[s]}$ rate of flow of product *i* transferred from distribution centre *k* to customer zone *l* during time period *t* under scenario *s*

W_m capacity of warehouse *m*

Binary variables

PW_m 1 if warehouse *m* is established, 0 otherwise

PDC_k 1 if distribution centre *k* is established, 0 otherwise

$PWDC_{mk}$ 1 if material is transported from warehouse *m* to distribution centre *k*, 0 otherwise

$PDCL_{kl}$ 1 if material is transported from distribution centre *k* to customer zone *l*, 0 otherwise

$PWDC_{mkt}^{[s]}$ 1 if material is transported from warehouse *m* to distribution centre *k* during time period *t* under scenario *s*, 0 otherwise

$PDCL_{klt}^{[s]}$ 1 if material is transported from distribution centre *k* to customer zone *l* during time period *t* under scenario *s*, 0 otherwise

Greek letters

γ_{im} coefficient relating capacity of warehouse *m* to inventory of product *i* held

γ_{ik} coefficient relating capacity of distribution centre *k* to inventory of product *i* held

ρ_{ije} coefficient of rate of utilization resource *e* in plant *j* to produce product *i*

ψ_s probability of product demand scenario *s* occurring during the lifetime of the network

3.3.4 Constraints

Network structure constraints

The link between a warehouse *m* and a distribution centre *k* can exist only if warehouse *m* is also established:

$$\mathrm{PWDC}_{mk} \leq \mathrm{PW}_{m}, \forall\, m, k \tag{3.2}$$

It is sometimes required that certain distribution centres be served by a single warehouse (single sourcing). This can be enforced via the constraint:

$$\textstyle\sum_{m} \mathrm{PWDC}_{mk} = \mathrm{PDC}_{k}, \forall k \in \mathrm{K}^{SS} \tag{3.3}$$

If the distribution centre does not exist then its links with warehouses cannot exist either. This leads to the constraint:

$$\mathrm{PWDC}_{mk} \leq \mathrm{PDC}_{k}, \forall m, k \notin \mathrm{K}^{SS} \tag{3.4}$$

The above is written only for the distribution centres that are not single sourced. For the rest of the distribution centres constraint (3.3) already suffices.

The link between a distribution centre *k* and a customer zone *l* will exist only if the distribution centre *k* also exists:

$$\mathrm{PDCL}_{kl} \leq \mathrm{PDC}_{k}, \forall k, l \tag{3.5}$$

Some customer zones may be subject to a single sourcing constraint requiring that they be served by exactly one distribution centre:

$$\textstyle\sum_{k} \mathrm{PDCL}_{kl} = 1, \forall l \in \mathrm{L}^{SS} \tag{3.6}$$

Logical constrains for transportation flows

Flow of material *i* from plant *j* to warehouse *m* can take place only if warehouse *m* exists:

$$\mathrm{Q}_{ijmt}^{[s]} \leq \mathrm{Q}_{ijm}^{[s],max} \mathrm{PW}_{m}, \forall i, j, m, t, s = 1, \cdots, \mathrm{NS} \tag{3.7}$$

The above constraints are enforced over both each scenario *s* and each time period *t*. Flow of material *i* from warehouse *m* to distribution centre *k* can take place only if the corresponding connection exists:

$$Q_{imkt}^{[s]} \leq Q_{imk}^{[s],max} PWDC_{mk}, \forall i, m, k, t, s = 1, \cdots, NS \tag{3.8}$$

Flow of material i from distribution centre k to customer zone l can take place only if the corresponding connection exists:

$$Q_{iklt}^{[s]} \leq Q_{ikl}^{[s],max} PDCL_{kl}, \forall i, k, l, t, s = 1, \cdots, NS \tag{3.9}$$

Appropriate values for the upper bounds appearing on the right hand size of the above constraints can be obtained as described in Tsiakis et al. (2001). There is usually a minimum total flow rate of material (of whatever type) that is needed to justify the establishment of a transportation link between two locations in the network. This consideration leads to the following constraints:

$$\sum_i Q_{imkt}^{[s]} \geq Q_{mk}^{min} PWDC_{mk}, \forall m, k, t, s = 1, \cdots, NS \tag{3.10}$$

$$\sum_i Q_{iklt}^{[s]} \geq Q_{kl}^{min} PDCL_{kl}, \forall k, l, t, s = 1, \cdots, NS \tag{3.11}$$

for the links between a warehouse m and a distribution centre k, and between a distribution centre k and a customer zone l, respectively.

Material balances constraints

The mathematical model supposes that inventory may be kept at different stages in the network. If no product inventories were held at the plants locations, the actual rate of production of product i by plant j would equal the total flow of this product from plant j to all warehouses m. However, if inventory of product i allowed to be held in plant j at time t, then the material balance on the plant over period t becomes:

$$I_{ijt}^{[s]} = I_{ij,t-1}^{[s]} + \left(P_{ijt}^{[s]} - \sum_m Q_{ijmt}^{[s]}\right) \Delta T_t, \forall i, j, t, s = 1, \cdots, NS \tag{3.12}$$

Constraint (3.12) states that the available inventory of product i held in plant j at the end of period t (left side of equation) is equal to the inventory held at the end of period *t-1* plus any product accumulated in the plant due to the production during the period, minus any product transported from the plant to warehouses during the same period. Since both production and transportation are expressed as flows of material over time (e.g. tonnes/week), we calculate the total amount of material during period [*t-1, t*] by multiplying these rates by the duration ΔT_t of time period t. Typically, the durations ΔT_t range from a few weeks to several months depending on the actual planning procedures of the corporation.

Similarly, we can formulate the following constraints for the warehouses and distribution centres:

$$\mathrm{I}_{imt}^{[s]} = \mathrm{I}_{im,t-1}^{[s]} + \left(\sum_j \mathrm{Q}_{ijmt}^{[s]} - \sum_k \mathrm{Q}_{imkt}^{[s]}\right) \Delta\mathrm{T}_t, \forall i, m, t, s = 1, \cdots, \mathrm{NS} \qquad (3.13)$$

$$\mathrm{I}_{ikt}^{[s]} = \mathrm{I}_{ik,t-1}^{[s]} + \left(\sum_m \mathrm{Q}_{imkt}^{[s]} - \sum_l \mathrm{Q}_{iklt}^{[s]}\right) \Delta\mathrm{T}_t, \forall i, k, t, s = 1, \cdots, \mathrm{NS} \qquad (3.14)$$

Customer zones do not normally hold significant amounts of inventory. Consequently, the total flow of each product *i* received by each customer zone *l* from the distribution centres is assumed to be equal to the corresponding market demand:

$$\sum_k \mathrm{Q}_{iklt}^{[s]} = \mathrm{D}_{ilt}^{[s]}, \forall i, l, t, s = 1, \cdots, \mathrm{NS} \qquad (3.15)$$

The initial inventories $\mathrm{I}_{ij0}^{[s]}$, $\mathrm{I}_{im0}^{[s]}$, and $\mathrm{I}_{ik0}^{[s]}$ are assume to be given as part of the specification of each distinct scenario *s*.

Production resources constraints

An important issue in the operation of the distribution network is the ability of the manufacturing plants to cover the demands of the customers as expressed through the orders received from the warehouses. The rate of production of each product at any plant cannot exceed certain limits. Thus, there is always a minimum production capacity for any one product; moreover there is often a minimum production rate that must be maintained while the plant is operating. All the above are expressed through the following constraint which is enforced for each and every scenario *s* and each time period *t*:

$$\mathrm{P}_{ijt}^{[s],min} \le \mathrm{P}_{ijt}^{[s]} \le \mathrm{P}_{ijt}^{[s],max}, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \qquad (3.16)$$

It is common in many manufacturing sites for some resources (equipment, utilities, manpower, etc.) to be used by several production lines and at different stages of the production of each product. This share usage limits the availability of the resource that can be used for any one purpose as expressed by the following constraint:

$$\sum_i \rho_{ije} \mathrm{P}_{ijt}^{[s]} \le \mathrm{R}_{je}, \forall j, e, t, s = 1, \cdots, \mathrm{NS} \qquad (3.17)$$

The coefficient ρ_{ije} express the amount of resource *e* used by plant *j* to produce a unit amount of product *i*, while R_{je} represents the total rate of availability of resource *e* at plant *j*.

Capacity constraints for warehouses and distribution centres

One of the most significant issues during the design and the life time of the network are the capacities of warehouses and distribution centres. These amounts specify the quantity of products, which can be stored there temporary, before their conveyance at the market.

The capacity of a warehouse *m* generally has to lie between given lower and upper bounds, W_m^{min} and W_m^{max} provided, of course that the warehouse is actually established (i.e. $\mathrm{PW}_m = 1$):

$$\mathrm{W}_m^{min}\mathrm{PW}_m \leq \mathrm{W}_m \leq \mathrm{W}_m^{max}\mathrm{PW}_m, \forall m \quad (3.18)$$

Similar constraints apply to the capacities of distribution centres *k*:

$$\mathrm{D}_k^{min}\mathrm{PDC}_k \leq \mathrm{D}_k \leq \mathrm{D}_k^{max}\mathrm{PDC}_k, \forall k \quad (3.19)$$

The dynamic formulation of the model allows an arguably more precise characterization of these capacities in terms of the actual inventory being held. More specifically, the capacity of a warehouse or a distribution centre cannot be less than the combined inventory to be held there at any time period under each scenario. This leads to constraints of the form:

$$\mathrm{W}_m \geq \sum_i \gamma_{im}\mathrm{I}_{imt}^{[s]}, \forall m, t, s = 1, \cdots, \mathrm{NS} \quad (3.20)$$

$$\mathrm{D}_k \geq \sum_i \gamma_{ik}\mathrm{I}_{ikt}^{[s]}, \forall k, t, s = 1, \cdots, \mathrm{NS} \quad (3.21)$$

where γ_{im} and γ_{ik} are given coefficients expressing the amount of warehousing capacity required to hold a unit amount of a particular product *i* at a warehouse *m* or a distribution centre *k*, respectively.

Safety stock constraints

Maintaining a safety stock (also known as “buffer inventory”) is often desirable, providing a means of overcoming unforeseen production disturbances or unexpected product demands. In general, the higher the level of inventory, the better the customer service, with fewer stockouts. On the other hand, excess inventory causes higher operating costs. Consequently, safety stock is usually only as much as is necessary to keep the network functioning for a short period of time (e.g. from a few days to a week) in case of disruption at one or more of its nodes.

The need for safety stock can be expressed by the following constraints:

$$\mathrm{I}_{ijt}^{[s]} \geq \mathrm{I}_{ijt}^{[s],min}, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \tag{3.22}$$

$$\mathrm{I}_{imt}^{[s]} \geq \mathrm{I}_{imt}^{[s],min} \mathrm{PW}_m, \forall i, m, t, s = 1, \cdots, \mathrm{NS} \tag{3.23}$$

$$\mathrm{I}_{ikt}^{[s]} \geq \mathrm{I}_{ikt}^{[s],min} \mathrm{PDC}_k, \forall i, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.24}$$

The above constraints ensure that inventory is kept at warehouses or distribution centres only if these are established. We also note that the minimum inventory handling requirements may vary from scenario to scenario and from one time period to another. In fact they are often expressed as functions (e.g. constant multiples) of the corresponding material flows delivered by each plant, warehouse or distribution centre node to all other nodes that are served by it.

Since we assume constant rates of production, transportation and demand over each time period, inventories vary linearly with time during a period. Consequently, it suffices to enforce constraints (3.22)–(3.24) at the time period boundaries for them to hold at all times during the planning time horizon.

As explained above the amount of safety stock to be held at each plant, warehouse or distribution centre node is usually expressed in terms of a given number of days' equivalent of material flow delivered by the node to all nodes supplied by it. Here we assume that this number of days is the same for all nodes of the same type (e.g. plants, warehouses or distribution centres). Thus, the safety stock is given by:

$$\mathrm{I}_{ijt}^{[s],min} = \frac{\mathrm{n}^P}{7} \sum_m \mathrm{Q}_{ijmt}^{[s]}, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \tag{3.25}$$

$$\mathrm{I}_{imt}^{[s],min} = \frac{\mathrm{n}^W}{7} \sum_k \mathrm{Q}_{imkt}^{[s]}, \forall i, m, t, s = 1, \cdots, \mathrm{NS} \tag{3.26}$$

$$\mathrm{I}_{ikt}^{[s],min} = \frac{\mathrm{n}^{DC}}{7} \sum_l \mathrm{Q}_{iklt}^{[s]}, \forall i, j, k, s = 1, \cdots, \mathrm{NS} \tag{3.27}$$

where $\mathrm{n}^{DC}, \mathrm{n}^W, \mathrm{n}^P$ are the numbers of days equivalent for plants, warehouses and distribution centres, respectively, and the division by seven reflects the fact that all our material flows are expressed as tonnes per week. The right hand sides of equations (3.25)–(3.27) are used to replace the minimum inventory quantities appearing in the right hand sides of constraints (3.22)–(3.24), respectively. Initial inventories for each product and for each production plant are assumed to been known at a certain level.

Non-negativity constraints

All continuous variables must be non-negative:

$$\mathrm{P}_{ijt}^{[s]} \geq 0, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \tag{3.28}$$

$$\mathrm{I}_{ijt}^{[s]} \geq 0, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \tag{3.29}$$

$$\mathrm{I}_{imt}^{[s]} \geq 0, \forall i, m, t, s = 1, \cdots, \mathrm{NS} \tag{3.30}$$

$$\mathrm{I}_{ikt}^{[s]} \geq 0, \forall i, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.31}$$

$$\mathrm{Q}_{ijmt}^{[s]} \geq 0, \forall i, j, m, t, s = 1, \cdots, \mathrm{NS} \tag{3.32}$$

$$\mathrm{Q}_{imkt}^{[s]} \geq 0, \forall i, m, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.33}$$

$$\mathrm{Q}_{iklt}^{[s]} \geq 0, \forall i, k, l, t, s = 1, \cdots, \mathrm{NS} \tag{3.34}$$

$$\mathrm{W}_m \geq 0, \forall m \tag{3.35}$$

$$\mathrm{D}_k \geq 0, \forall k \tag{3.36}$$

3.3.5 Objective function components

The objective of the optimisation is to minimise the overall expected value of SCN's cost over a planning time horizon. This includes both (annualised) capital costs and operating costs, and lead to an objective function which includes the following five terms.

Fixed infrastructure cost

The infrastructure costs considered by our formulation are related to the establishment of a warehouse or a distribution centre at a candidate location. These costs are represented by the following objective function terms:

$$\sum_m \mathrm{C}_m^W \mathrm{PW}_m + \sum_k \mathrm{C}_k^D \mathrm{PDC}_k \tag{3.37}$$

The annualised fixed cost of establishing a warehouse at location *m*, denoted as C_m^W, is multiplied by the binary variable PW_m. Thus, only if the warehouse *m* is selected, the corresponding cost participates in the objective function. In a similar fashion, the annualised fixed cost of establishing a distribution centre at location *k* (C_k^D) is included in the objective function only if the binary variable PDC_k takes the value of one, meaning that the corresponding distribution centre is established.

We assume that the manufacturing plants are already established. Therefore, we do not consider the capital cost associated with their design and construction. We also ignore any infrastructure cost associated with the customer zones.

Production cost

The production cost is given by the product of the production rate $\mathrm{P}_{ijt}^{[s]}$, of product *i* in plant *j* at time period *t* under scenario *s*, and the unit production cost C_{ij}^P. The corresponding term in the objective function is of the form:

$$\sum_{i,j} \mathrm{C}_{ij}^P \, \mathrm{P}_{ijt}^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{3.38}$$

Material handling cost at warehouses and distribution centres

Material handling costs such as wages, extra packing, insurance contracts, electricity, etc. can usually be approximated as linear functions of the total throughput. They can be expressed as follows:

$$\sum_{i,m} C_{im}^{WH}\left(\sum_j Q_{ijmt}^{[s]}\right) + \sum_{i,k} C_{ik}^{DH}\left(\sum_m Q_{imkt}^{[s]}\right), \forall t, s = 1, \cdots, \mathrm{NS} \quad (3.39)$$

Inventory holding cost at different nodes

Since inventory may be kept at different stages in the network, a cost is associated with their management. In general, the cost incurred over a given time period *t* is proportional to the average amount of inventory held over this period. The average inventory is expressed by the arithmetic mean of the starting and finishing inventories for this period, as inventories vary linearly over each time period.

$$\sum_{i,j} C_{ijt}^{I}\frac{I_{ijt}^{[s]}+I_{ij,t-1}^{[s]}}{2} + \sum_{i,m} C_{imt}^{I}\frac{I_{imt}^{[s]}+I_{im,t-1}^{[s]}}{2} + \sum_{i,k} C_{ikt}^{I}\frac{I_{ikt}^{[s]}+I_{ik,t-1}^{[s]}}{2}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (3.40)$$

Transportation cost

The total transportation cost for product *i* during time period *t* under scenario *s*, is proportional to the amount of material transferred between echelons. Transportation costs included are those from production plants to warehouses, from warehouses to distribution centres, and from distribution centres to customer zones. Each one of these constituents are calculated as the product of unit transportation cost and the rate of flow transferred between successive nodes in the network. A more detailed modelling approach reflecting economies of scale can be found in Tsiakis et al. (2001).

$$\sum_{i,j,m} C_{ijm}^{TR} Q_{ijmt}^{[s]} + \sum_{i,m,k} C_{imk}^{TR} Q_{imkt}^{[s]} + \sum_{i,k,l} C_{ikl}^{TR} Q_{iklt}^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (3.41)$$

Objective function

The final form of the objective function is as follows:

$$
\begin{aligned}
\mathrm{OBJ}^1\!: \min \sum_t \Delta\mathrm{T}_t \left(\sum_m \mathrm{C}_m^W \, \mathrm{PW}_m + \sum_k \mathrm{C}_k^D \mathrm{PDC}_k \right) \\
+ \sum_{s=1}^{NS} \psi_S \Bigg(\sum_t \Delta\mathrm{T}_t \Bigg(\sum_{i,j} \mathrm{C}_{ij}^P \mathrm{P}_{ijt}^{[s]} + \sum_{i,m} \mathrm{C}_{im}^{WH} \left(\sum_j \mathrm{Q}_{ijmt}^{[s]} \right) + \sum_{i,k} \mathrm{C}_{ik}^{DH} \left(\sum_m \mathrm{Q}_{imkt}^{[s]} \right) \\
+ \sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]} + \sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]} + \sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]} + \sum_{i,j} \mathrm{C}_{ijt}^{I} \frac{\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{ij,t-1}^{[s]}}{2} \\
+ \sum_{i,m} \mathrm{C}_{imt}^{I} \frac{\mathrm{I}_{imt}^{[s]} + \mathrm{I}_{im,t-1}^{[s]}}{2} + \sum_{i,k} \mathrm{C}_{ikt}^{I} \frac{\mathrm{I}_{ikt}^{[s]} + \mathrm{I}_{ik,t-1}^{[s]}}{2} \Bigg) \Bigg)
\end{aligned}
$$

It should be noted that the objective function reflects actual total costs incurred over the planning horizon rather than rate of expenditure (i.e. it is measured in Relative Money Units (RMU) instead of RMU/week). The annualised capital costs are multiplied by the total length of the time horizon under consideration $\sum_t \Delta\mathrm{T}_t$. The rate of operating expenditure varies from one time period to the next. Consequently the operating cost in each period *t* is multiplied by the corresponding duration $\Delta\mathrm{T}_t$.

3.3.6 Solution approach

The above problem, which considers the optimal design of multi-echelon SCNs under transient demand conditions, is formulated mathematically as a MILP problem that includes objective function OBJ^1 and constraints (3.1)–(3.36) and is solved by using standard branch-and-bound techniques.

3.3.7 Scenario-dependent distribution network

The formulation presented above was based on the assumption that the structure of the distribution network (i.e. the transportation links between warehouses, distribution centres and customer zones) was independent of the scenario. In many cases, this is unnecessary since the costs associated with the establishment of a transportation link are relative small. This is especially the case when transportation is outsourced to third parties. In such cases, it could be allowed to the network of transportation links to vary both over time and depending on the scenario instead of treating these decisions as "here-and-now" variables to be fixed once and for all at the design stage. This effectively allows for some reconfiguration of the SCN during operation.

The required changes in the mathematical model formulation are minimal. More, specifically, the binary variables PWDC_{mk} and PDCL_{kl} will now have a superscript [*s*] and a subscript [*t*] to denote that they can change for each possible scenario and during each time period of the operation of the network.

The constraints that need to change are:

$$\mathrm{PWDC}_{mkt}^{[s]} \leq \mathrm{PW}_m , \forall\, m, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.2'}$$

$$\textstyle\sum_m \mathrm{PWDC}_{mkt}^{[s]} = \mathrm{PDC}_k, \forall k \in \mathrm{K}^{SS}, t, s = 1, \cdots, \mathrm{NS} \tag{3.3'}$$

$$\mathrm{PWDC}_{mkt}^{[s]} \leq \mathrm{PDC}_k, \forall m, k \notin \mathrm{K}^{SS}, t, s = 1, \cdots, \mathrm{NS} \tag{3.4'}$$

$$\mathrm{PDCL}_{klt}^{[s]} \leq \mathrm{PDC}_k, \forall k, l, t, s = 1, \cdots, \mathrm{NS} \tag{3.5'}$$

$$\textstyle\sum_k \mathrm{PDCL}_{klt}^{[s]} = 1, \forall l \in \mathrm{L}^{SS}, t, s = 1, \cdots, \mathrm{NS} \tag{3.6'}$$

$$\mathrm{Q}_{imkt}^{[s]} \leq \mathrm{Q}_{imk}^{[s],max} \mathrm{PWDC}_{mkt}^{[s]}, \forall i, m, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.8'}$$

$$\mathrm{Q}_{iklt}^{[s]} \leq \mathrm{Q}_{ikl}^{[s],max} \mathrm{PDCL}_{klt}^{[s]}, \forall i, k, l, t, s = 1, \cdots, \mathrm{NS} \tag{3.9'}$$

$$\textstyle\sum_i \mathrm{Q}_{imkt}^{[s]} \geq \mathrm{Q}_{mk}^{min} \mathrm{PWDC}_{mkt}^{[s]}, \forall m, k, t, s = 1, \cdots, \mathrm{NS} \tag{3.10'}$$

$$\textstyle\sum_i \mathrm{Q}_{iklt}^{[s]} \geq \mathrm{Q}_{kl}^{min} \mathrm{PDCL}_{klt}^{[s]}, \forall k, l, t, s = 1, \cdots, \mathrm{NS} \tag{3.11'}$$

This option gives the network an additional degree of flexibility. Only the locations of warehouses and distribution centres are constant through the operation of the system, while the links between nodes may be re-allocated in every time period and scenario in order to satisfy customer demand in the most coast-efficient manner.

3.4 A case study

3.4.1 Background

In order to evaluate the applicability of the MILP model M1 presented in the previous section we study a multinational company located in the United Kingdom and operating in the foods, home and personal care industry. We consider a European wide production and distribution network comprising of three manufacturing plants producing 14 different types of products and located in three different European countries, namely the United Kingdom, Spain and Italy (see Figure 3-3).

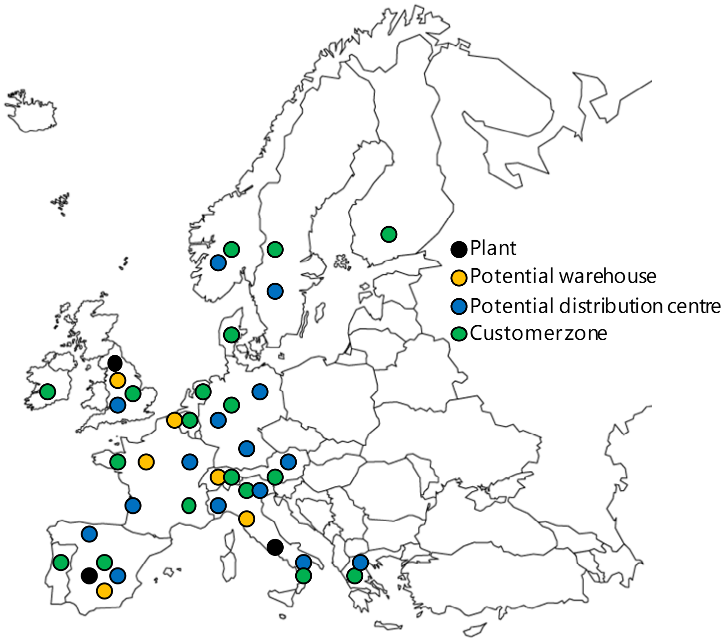


Figure 3-3: The case study SCN

Product demands are such that Europe can be divided into 18 customer zones located in 16 different countries. The objective is the establishment of a sufficient network of warehouses and distribution centres to cover the whole market. The distribution centres can be located anywhere in 15 countries, and are to be supplied by up to six warehouses, the location of which is also to be chosen among six candidate places.

Because of the fact that customer demand is both uncertain and time-varying the scenario-based approach is employed. Last but not least, inventories are held in different stages in the network in low or high levels, thus we examine two case studies. All data provided in the work of Tsiakis et al. (2001).

Manufacturing plants and production procedure

The three manufacturing plants are already established in specified European countries and produce 14 types of different products. Each plant produces several products using a number of shared production resources. However, no single plant produces the entire range of products. Table 3-1 shows the maximum production rate $\mathrm{P}_{ijt}^{[s],max}$ of each manufacturing plant, whereas the corresponding minimum production rate is assumed to be zero (i.e. $\mathrm{P}_{ijt}^{[s],min} = 0, \forall i, j$). In Table 3-2 all columns give the values of the ρ_{ije} coefficient, while the last column represents the total availability of resource e in manufacturing plant j (R_{je}). The unit production cost is indicated in Table 3-3.

Table 3-1: Maximum production capacity of plant *j* for product *i**

Plant	Product (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
j_1	158	2268	1701	1512	0	812	642	482	320	504	0	661	441	221
j_2	0	1411	1058	1328	996	664	664	0	0	0	530	496	330	0
j_3	972	778	607	540	0	416	416	312	208	0	403	0	270	0

* There is no difference among several scenarios and time periods.
Note: t/w means tonnes per week.

Table 3-2: Utilization & availability of resource *e* for product *i* in plant *j**

Plant	Shared resource utilization coefficient ρ_{ije} (h/t)														R_{je} (h/w)
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	
j_1-e_1										0.2381					120
j_1-e_2		0.0463	0.0617	0.0694											105
j_1-e_3							0.1634	0.2178	0.3268						105
j_1-e_4												0.2267	0.3401	0.6802	150
j_1-e_5						0.1292									105
j_1-e_6	0.6667														105
j_2-e_1											0.1984	0.2118	0.3174		105
j_2-e_2				0.0793	0.1054	0.1582	0.1582								105
j_2-e_3		0.0740	0.1000												105
j_3-e_1			0.1976	0.2222											120
j_3-e_2						0.3968	0.3968	0.5291	0.7936						165
j_3-e_3	0.1200	0.1543													120
j_3-e_4											0.2976		0.4444		120

* There is no difference among several scenarios and time periods.
Note: h/t means hours per tonne and h/w means hours per week.

Table 3-3: Unit production cost of product *i* in plant *j**

Plant	Unit production cost (RMU/t)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
j_1	61.27	61.27	61.27	61.27	61.27	61.27	256.90	256.90	256.90	61.27	256.90	256.90	256.90	256.90
j_2	59.45	59.45	59.45	59.45	59.45	59.45	268.50	268.50	268.50	59.45	268.50	268.50	268.50	268.50
j_3	61.44	61.44	61.44	61.44	61.44	61.44	270.80	270.80	270.80	61.44	270.80	270.80	270.80	270.80

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Warehouses and distribution centres

All products after their production go to warehouses, where they will be stored and then placed at distribution centres. Warehouses will be selected among six candidate locations and distribution centres among 15 possible locations. Each warehouse and distribution centre cannot keep more than 14,000 tonne/week (W_m^{max}) and 7000 (D_k^{max}) tonne/week, respectively. On the other hand, there are no requirements for minimum material handling capacities ($W_m^{min} = 0$ and $D_k^{min} = 0$). Despite the fact that capacities are the same, fixed infrastructure costs vary for each node, whereas material handling costs are the same for all products but may differ from place to place, as shown in Table 3-4. The coefficients γ_{im} and γ_{ik} which show the capacity of each warehouse m or distribution centre k that is required for the storage of a product i are equal to one.

Table 3-4: Infrastructure & material handling costs of warehouse *m* and distribution centre *k**

Warehouse	Infrastructure cost (C_m^W) (RMU/w)	Material handling cost (C_{im}^{WH}) (RMU/t)
m_1	10,000	4.25
m_2	5000	4.55
m_3	4000	4.98
m_4	6000	4.93
m_5	6500	4.06
m_6	4000	5.28
Distribution centre	**Infrastructure cost (C_k^D) (RMU/w)**	**Material handling cost (C_{ik}^{DH}) (RMU/t)**
k_1	10,000	4.25
k_2	5000	4.55
k_3	4000	4.98
k_4	6000	4.93
k_5	6500	4.85
k_6	4000	3.90
k_7	6000	4.06
k_8	4000	3.08
k_9	5000	6.00
k_{10}	3000	4.85
k_{11}	4500	4.12
k_{12}	7000	5.66
k_{13}	9000	5.28
k_{14}	5500	4.95
k_{15}	8500	4.83

* There is no difference among several scenarios and time periods.
Note: RMU/w means RMU per week and RMU/t means RMU per tonne.

Product demand

A planning horizon comprising three four-week time periods is considered ($\Delta T_1 = \Delta T_2 = \Delta T_3 = 4$ weeks). Product demands over the first period are assumed to be known with certainty, and are shown in Table 3-5. However, there are two distinctly different predictions for demands over the second period, shown in Tables 3-6 and 3-7, respectively. Moreover, each of these demand predictions for the second period leads to two distinct demand predictions for the third period (see Tables 3-8 to 3-11).

Table 3-5: Demand for product *i* from customer zone *l* over the first period (all scenarios)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	18	0	0	506	0	452	0	0	43	0	0	0	120	34
l_2	0	499	155	203	76	0	30	0	0	0	20	0	0	0
l_3	0	155	0	166	0	66	17	0	0	0	0	0	15	0
l_4	15	0	126	0	0	0	5	27	0	0	0	25	0	0
l_5	0	0	92	0	0	0	0	0	21	0	0	0	50	0
l_6	0	0	0	0	0	68	0	0	20	0	0	0	10	10
l_7	0	14	0	40	0	0	0	0	34	0	0	0	68	0
l_8	0	0	0	45	0	23	0	0	5	0	0	0	0	0
l_9	0	0	0	0	0	0	52	0	7	0	0	0	0	0
l_{10}	0	0	0	17	0	0	0	0	5	0	0	0	16	0
l_{11}	0	0	0	31	0	0	0	0	0	0	0	0	15	0
l_{12}	0	31	0	0	0	0	13	0	0	38	0	0	0	0
l_{13}	0	21	0	0	0	0	15	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	7	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	10	0	0	0	15	0	0	0
l_{16}	15	0	68	0	0	0	5	20	0	0	0	20	0	0
l_{17}	0	103	0	110	0	44	12	0	0	0	0	0	13	0
l_{18}	0	0	0	0	0	0	0	0	0	266	0	0	0	0

Note: t/w means tonnes per week.

Table 3-6: Demand for product *i* from customer zone *l* over the second period (scenario 1-2)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	14	0	0	547	0	412	0	0	46	0	0	0	94	30
l_2	0	612	144	248	83	0	33	0	0	0	24	0	0	0
l_3	0	117	0	202	0	70	21	0	0	0	0	0	12	0
l_4	17	0	157	0	0	0	6	25	0	0	0	27	0	0
l_5	0	0	97	0	0	0	0	0	19	0	0	0	56	0
l_6	0	0	0	0	0	65	0	0	16	0	0	0	10	11
l_7	0	14	0	40	0	0	0	0	42	0	0	0	63	0
l_8	0	0	0	51	0	25	0	0	5	0	0	0	0	0
l_9	0	0	0	0	0	0	49	0	8	0	0	0	0	0
l_{10}	0	0	0	17	0	0	0	0	5	0	0	0	13	0
l_{11}	0	0	0	33	0	0	0	0	0	0	0	0	11	0
l_{12}	0	26	0	0	0	0	14	0	0	38	0	0	0	0
l_{13}	0	21	0	0	0	0	11	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	8	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	11	0	0	0	14	0	0	0
l_{16}	11	0	51	0	0	0	5	24	0	0	0	20	0	0
l_{17}	0	124	0	135	0	36	14	0	0	0	0	0	20	0
l_{18}	0	0	0	0	0	0	0	0	0	241	0	0	0	0

Note: t/w means tonnes per week.

Table 3-7: Demand for product *i* from customer zone *l* over the second period (scenario 3-4)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	18	0	0	436	0	568	0	0	54	0	0	0	149	31
l_2	0	633	154	195	62	0	25	0	0	0	26	0	0	0
l_3	0	172	0	189	0	58	16	0	0	0	0	0	15	0
l_4	14	0	159	0	0	0	6	33	0	0	0	29	0	0
l_5	0	0	74	0	0	0	0	0	17	0	0	0	57	0
l_6	0	0	0	0	0	57	0	0	18	0	0	0	11	12
l_7	0	16	0	41	0	0	0	0	44	0	0	0	67	0
l_8	0	0	0	46	0	19	0	0	6	0	0	0	0	0
l_9	0	0	0	0	0	0	54	0	6	0	0	0	0	0
l_{10}	0	0	0	22	0	0	0	0	4	0	0	0	20	0
l_{11}	0	0	0	28	0	0	0	0	0	0	0	0	14	0
l_{12}	0	29	0	0	0	0	12	0	0	45	0	0	0	0
l_{13}	0	20	0	0	0	0	15	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	8	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	10	0	0	0	19	0	0	0
l_{16}	13	0	62	0	0	0	4	19	0	0	0	21	0	0
l_{17}	0	97	0	122	0	51	13	0	0	0	0	0	16	0
l_{18}	0	0	0	0	0	0	0	0	0	327	0	0	0	0

Note: t/w means tonnes per week.

Table 3-8: Demand for product *i* from customer zone *l* over the third period (scenario 1)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	19	0	0	528	0	559	0	0	50	0	0	0	106	40
l_2	0	657	164	279	82	0	42	0	0	0	22	0	0	0
l_3	0	113	0	205	0	95	28	0	0	0	0	0	12	0
l_4	21	0	196	0	0	0	6	30	0	0	0	33	0	0
l_5	0	0	112	0	0	0	0	0	23	0	0	0	65	0
l_6	0	0	0	0	0	77	0	0	14	0	0	0	15	16
l_7	0	16	0	45	0	0	0	0	46	0	0	0	79	0
l_8	0	0	0	70	0	24	0	0	6	0	0	0	0	0
l_9	0	0	0	0	0	0	50	0	7	0	0	0	0	0
l_{10}	0	0	0	17	0	0	0	0	6	0	0	0	12	0
l_{11}	0	0	0	44	0	0	0	0	0	0	0	0	13	0
l_{12}	0	0	0	0	0	0	17	0	0	51	0	0	0	0
l_{13}	0	27	0	0	0	0	13	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	11	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	13	0	0	0	14	0	0	0
l_{16}	14	0	56	0	0	0	5	29	0	0	0	27	0	0
l_{17}	0	160	0	172	0	35	20	0	0	0	0	0	12	0
l_{18}	0	0	0	0	0	0	0	0	0	331	0	0	0	0

Note: t/w means tonnes per week.

Table 3-9: Demand for product *i* from customer zone *l* over the third period (scenario 2)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	18	0	0	761	0	551	0	0	55	0	0	0	125	37
l_2	0	706	209	282	104	0	38	0	0	0	34	0	0	0
l_3	0	152	0	233	0	88	24	0	0	0	0	0	15	0
l_4	19	0	164	0	0	0	7	30	0	0	0	35	0	0
l_5	0	0	115	0	0	0	0	0	27	0	0	0	80	0
l_6	0	0	0	0	0	81	0	0	16	0	0	0	11	15
l_7	0	15	0	42	0	0	0	0	44	0	0	0	82	0
l_8	0	0	0	65	0	30	0	0	6	0	0	0	0	0
l_9	0	0	0	0	0	0	67	0	8	0	0	0	0	0
l_{10}	0	0	0	21	0	0	0	0	7	0	0	0	15	0
l_{11}	0	0	0	37	0	0	0	0	0	0	0	0	14	0
l_{12}	0	0	0	0	0	0	14	0	0	39	0	0	0	0
l_{13}	0	22	0	0	0	0	16	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	10	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	16	0	0	0	18	0	0	0
l_{16}	12	0	72	0	0	0	6	33	0	0	0	25	0	0
l_{17}	0	169	0	194	0	35	15	0	0	0	0	0	13	0
l_{18}	0	0	0	0	0	0	0	0	0	329	0	0	0	0

Note: t/w means tonnes per week.

Table 3-10: Demand for product *i* from customer zone *l* over the third period (scenario 3)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	24	0	0	420	0	772	0	0	58	0	0	0	169	40
l_2	0	680	175	220	62	0	32	0	0	0	24	0	0	0
l_3	0	165	0	191	0	78	22	0	0	0	0	0	16	0
l_4	17	0	198	0	0	0	6	41	0	0	0	35	0	0
l_5	0	0	85	0	0	0	0	0	21	0	0	0	65	0
l_6	0	0	0	0	0	67	0	0	16	0	0	0	15	16
l_7	0	18	0	46	0	0	0	0	48	0	0	0	84	0
l_8	0	0	0	63	0	18	0	0	8	0	0	0	0	0
l_9	0	0	0	0	0	0	55	0	6	0	0	0	0	0
l_{10}	0	0	0	21	0	0	0	0	6	0	0	0	19	0
l_{11}	0	0	0	37	0	0	0	0	0	0	0	0	16	0
l_{12}	0	0	0	0	0	0	15	0	0	60	0	0	0	0
l_{13}	0	25	0	0	0	0	18	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	11	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	12	0	0	0	19	0	0	0
l_{16}	16	0	68	0	0	0	4	23	0	0	0	27	0	0
l_{17}	0	124	0	155	0	50	18	0	0	0	0	0	16	0
l_{18}	0	0	0	0	0	0	0	0	0	448	0	0	0	0

Note: t/w means tonnes per week.

Table 3-11: Demand for product *i* from customer zone *l* over the third period (scenario 4)

Customer zone	Product demand (t/w)													
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}
l_1	24	0	0	606	0	760	0	0	64	0	0	0	198	37
l_2	0	730	223	222	78	0	29	0	0	0	37	0	0	0
l_3	0	222	0	218	0	72	19	0	0	0	0	0	19	0
l_4	15	0	165	0	0	0	7	41	0	0	0	37	0	0
l_5	0	0	88	0	0	0	0	0	24	0	0	0	80	0
l_6	0	0	0	0	0	71	0	0	18	0	0	0	11	16
l_7	0	17	0	43	0	0	0	0	45	0	0	0	87	0
l_8	0	0	0	59	0	23	0	0	7	0	0	0	0	0
l_9	0	0	0	0	0	0	73	0	7	0	0	0	0	0
l_{10}	0	0	0	27	0	0	0	0	6	0	0	0	24	0
l_{11}	0	0	0	30	0	0	0	0	0	0	0	0	18	0
l_{12}	0	0	0	0	0	0	12	0	0	46	0	0	0	0
l_{13}	0	21	0	0	0	0	21	0	0	0	0	0	0	0
l_{14}	0	0	0	0	0	0	0	9	0	0	0	0	0	0
l_{15}	0	0	0	0	0	0	14	0	0	0	24	0	0	0
l_{16}	14	0	87	0	0	0	5	26	0	0	0	25	0	0
l_{17}	0	131	0	174	0	50	14	0	0	0	0	0	18	0
l_{18}	0	0	0	0	0	0	0	0	0	446	0	0	0	0

Note: t/w means tonnes per week.

Overall four distinct scenarios (i.e. $s = 1, \cdots, 4$) are considered and are organised in a tree structure of the type shown in Figure 3-1. The formulation of Section 3.2 is directly applicable to this situation, provided that:

- ✓ The operational variables of all four scenarios are treated as identical in the first time period, e.g.
$$\mathrm{P}_{ij1}^{[1]} = \mathrm{P}_{ij1}^{[2]} = \mathrm{P}_{ij1}^{[3]} = \mathrm{P}_{ij1}^{[4]}, \forall i, j$$
- ✓ The operational variables of scenarios 1 and 2 are treated as identical in the second time period, e.g.
$$\mathrm{P}_{ij2}^{[1]} = \mathrm{P}_{ij2}^{[2]}, \forall i, j$$
- ✓ The operational variables of scenarios 3 and 4 are treated as identical in the second time period, e.g.
$$\mathrm{P}_{ij2}^{[3]} = \mathrm{P}_{ij2}^{[4]}, \forall i, j$$

In practice the above inequalities are used to eliminate a priori a large proportion of the problem variables. All four scenarios are assumed to be equally probable ($\psi_1 = \psi_2 = \psi_3 = \psi_4 = 0.25$).

Transportation procedure and cost

The SCN cannot transfer between two nodes more than 100,000 products per each time period. Transportation costs are independent from economies of scale and are provided in Tables 3-12 to 3-14.

Table 3-12: Unit transportation cost between plant *j* and warehouse *m**

Plant	Warehouse (RMU/t)					
	m_1	m_2	m_3	m_4	m_5	m_6
			For products i_1-i_6 and i_{10}			
j_1	1.24	58.56	62.30	26.16	17.44	36.13
j_2	60.82	1.68	70.96	43.93	70.96	55.76
j_3	76.16	79.21	1.52	54.83	68.54	41.12
			For products i_7-i_9			
j_1	1.35	63.46	67.51	28.35	18.90	39.15
j_2	82.70	2.29	96.48	59.72	96.48	75.81
j_3	94.90	98.69	1.89	68.32	85.41	51.24
			For products i_{11}-i_{14}			
j_1	1.46	68.88	73.28	30.77	20.51	42.50
j_2	79.69	2.21	92.97	57.55	92.97	73.05
j_3	92.82	96.53	1.85	66.83	83.54	50.12

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Table 3-13: Unit transportation cost between warehouse *m* and distribution centre *k**

Warehouse	Distribution centre (RMU/t)														
	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	k_{15}
								For products i_1-i_6 and i_{10}							
m_1	0	74.40	76.13	25.96	69.21	29.41	17.30	117.66	44.99	110.74	76.13	12.11	39.79	64.02	60.56
m_2	58.85	0	62.96	45.16	109.49	69.80	67.06	94.44	90.33	145.08	17.79	60.22	52.01	108.12	72.54
m_3	72.83	76.14	0	49.66	94.35	99.32	62.90	43.04	79.45	129.12	94.35	62.90	33.10	104.29	28.14
m_4	28.54	62.78	57.08	0	87.52	58.98	32.34	106.55	62.78	135.09	72.30	22.83	19.02	89.42	49.47
m_5	16.51	73.58	57.06	25.52	48.05	37.54	0	93.10	25.52	84.09	78.08	7.50	30.03	45.05	42.04
m_6	69.52	67.78	34.76	17.38	78.21	69.52	34.76	79.95	59.09	121.66	78.21	33.02	0	83.42	27.80
								For products i_7-i_9							
m_1	0	75.28	77.03	26.26	70.02	29.76	17.50	119.04	45.51	112.04	77.03	12.25	40.26	64.77	61.27
m_2	60.87	0	65.12	46.71	113.25	72.20	69.36	97.68	93.43	150.06	18.40	62.29	53.79	111.84	75.03
m_3	90.75	94.88	0	61.88	117.57	123.76	78.38	53.63	99.00	160.89	117.57	78.38	41.25	129.95	35.06
m_4	28.88	63.54	57.77	0	88.58	59.58	32.73	107.83	63.54	136.72	73.17	23.10	19.25	90.50	50.06
m_5	17.90	79.77	61.86	27.67	52.09	40.70	0	100.93	27.67	91.16	84.65	8.14	32.56	48.84	45.58
m_6	86.62	84.46	43.31	21.65	97.45	86.62	43.31	99.62	73.63	151.59	97.45	41.14	0	103.95	34.65
								For products i_{11}-i_{14}							
m_1	0	69.15	70.78	24.14	64.32	27.33	16.08	109.35	41.81	102.92	70.76	11.25	36.98	59.50	56.28
m_2	69.66	0	74.52	53.46	129.61	82.63	79.38	111.79	106.93	171.74	21.06	71.28	61.56	127.99	85.87
m_3	92.01	96.19	0	62.73	119.19	125.47	79.46	54.37	100.37	163.11	119.19	79.46	41.82	131.74	35.55
m_4	26.53	58.37	53.07	0	81.37	54.83	30.07	99.06	58.37	125.59	67.2	21.22	17.69	83.14	45.99
m_5	20.49	91.29	70.80	31.67	59.62	46.58	0	115.51	31.67	104.33	96.88	9.31	37.26	55.89	52.16
m_6	87.82	85.63	43.91	21.95	98.80	87.82	43.91	85.70	63.34	130.42	83.84	35.40	0	89.43	35.13

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Table 3-14: Unit transportation cost between distribution centre *k* and customer zone *l**

Distribution centre	Customer zone (RMU/t)																	
	l_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	l_{10}	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	L_{18}
	For products i_1-i_6 and i_{10}																	
k_1	0	75.61	54.51	12.30	70.34	29.89	17.58	119.57	45.72	112.54	77.37	12.30	40.44	65.06	61.54	45.72	100.23	38.68
k_2	73.55	0	78.68	73.55	136.84	87.23	83.81	118.02	112.89	181.31	22.23	75.26	64.99	135.12	90.65	34.21	71.84	94.07
k_3	73.28	76.61	21.65	49.96	94.93	99.93	63.28	43.30	79.94	129.90	94.93	63.28	33.31	104.92	28.31	51.63	21.65	58.29
k_4	26.58	58.47	53.16	14.17	81.51	54.93	30.12	99.23	58.47	125.81	67.33	21.26	17.72	83.28	46.07	54.93	17.72	40.75
k_5	77.16	154.33	109.96	84.88	0	90.67	59.80	136.97	27.00	48.23	160.12	69.45	86.81	21.22	77.16	106.10	131.18	50.15
k_6	27.08	84.65	79.57	38.93	79.57	0	42.32	143.90	57.56	118.51	77.87	38.93	67.72	67.72	88.03	67.72	126.97	64.33
k_7	19.97	88.99	67.19	25.42	58.11	45.40	0	112.60	30.87	101.70	94.44	9.08	36.32	54.48	50.58	45.40	94.44	21.79
k_8	118.02	121.49	64.22	109.34	123.23	147.53	107.61	0	116.29	149.27	142.32	109.34	79.84	137.12	60.74	86.78	27.77	93.72
k_9	42.02	106.72	61.44	48.51	22.63	54.98	27.49	108.34	0	64.68	109.96	35.57	54.98	24.25	53.36	67.91	85.70	24.25
k_{10}	107.82	178.57	116.24	117.92	42.11	117.92	94.34	144.88	67.38	0	181.94	104.45	117.92	50.54	104.45	134.77	144.88	84.23
k_{11}	75.72	22.37	87.77	67.12	142.85	79.17	89.49	141.13	117.03	185.87	0	79.17	79.17	137.68	104.98	60.23	115.31	103.26
k_{12}	11.91	74.91	44.26	13.62	61.29	39.15	8.51	107.26	37.45	105.56	78.31	0	30.64	61.29	49.37	39.15	88.53	25.53
k_{13}	69.11	67.38	13.82	29.37	77.75	69.11	34.55	79.47	58.74	120.94	77.75	32.82	0	82.93	27.64	19.00	58.74	34.55
k_{14}	63.10	134.74	88.69	71.63	18.76	68.22	51.16	134.74	25.58	51.16	136.44	61.40	81.86	0	80.16	95.51	127.92	51.16
k_{15}	56.62	85.60	17.76	50.06	64.60	83.98	45.22	56.52	53.29	100.13	98.52	46.83	25.84	75.90	0	41.99	45.22	30.68

* There is no difference among several scenarios and time periods.

Note: RMU/t means RMU per tonne.

Table 3-14 (continue): Unit transportation cost between distribution centre *k* and customer zone *l**

Distribution centre	Customer zone (RMU/t)																	
	l_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	l_{10}	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	L_{18}
	For products i_7-i_9																	
k_1	0	73.12	52.71	11.90	68.02	28.90	17.00	115.63	44.21	108.83	74.82	11.90	39.11	62.91	59.51	44.21	96.92	37.41
k_2	73.20	0	78.31	73.20	136.20	86.82	83.42	117.47	12.36	180.46	22.13	74.91	64.69	134.49	90.23	34.05	71.50	93.63
k_3	81.65	85.36	24.12	55.67	105.78	111.34	70.52	48.25	89.07	144.75	105.78	70.52	37.11	116.91	31.54	57.52	24.12	64.95
k_4	24.76	54.48	49.53	13.20	75.95	51.18	28.06	92.46	54.48	117.22	62.74	19.81	16.51	77.60	42.92	51.18	16.51	37.97
k_5	77.52	155.04	110.47	85.27	0	91.09	60.08	137.60	27.13	48.45	160.86	69.77	87.21	21.31	77.52	106.59	131.79	50.39
k_6	32.65	102.06	95.93	46.94	95.93	0	51.03	173.50	69.40	142.88	93.89	46.94	81.64	81.64	106.14	81.64	153.09	77.56
k_7	19.54	87.05	65.73	24.87	56.85	44.41	0	110.15	30.20	99.49	92.38	8.88	35.53	53.30	49.74	44.41	92.38	21.32
k_8	127.18	130.92	69.20	117.83	132.79	158.98	115.96	0	125.31	160.85	153.37	117.83	86.03	147.76	65.46	93.52	29.92	101.00
k_9	48.45	123.01	70.82	55.91	26.09	63.36	31.68	124.87	0	74.55	126.73	41.00	63.36	27.95	61.50	78.27	98.78	27.95
k_{10}	111.91	185.36	120.66	122.40	43.71	122.40	97.92	150.38	69.94	0	188.85	108.41	122.40	52.46	108.41	139.89	150.38	87.43
k_{11}	81.65	24.12	94.64	72.37	154.03	85.36	96.50	152.17	126.19	200.42	0	85.36	85.36	148.46	113.20	64.95	124.33	11.34
k_{12}	12.44	78.21	46.21	14.22	63.99	40.88	8.88	111.98	39.10	110.21	81.76	0	31.99	63.99	51.55	40.88	92.43	26.66
k_{13}	58.96	57.48	11.79	25.05	66.33	58.96	29.48	67.80	50.11	103.18	66.33	28.00	0	70.75	23.58	16.21	50.11	29.48
k_{14}	60.11	128.35	84.48	68.23	17.87	64.98	48.74	128.35	24.37	48.74	129.97	58.48	77.98	0	76.36	90.98	121.85	48.74
k_{15}	60.97	92.32	19.16	54.00	69.68	90.58	48.77	60.97	57.48	108.00	106.26	50.51	27.87	81.87	0	45.29	48.77	33.09

* There is no difference among several scenarios and time periods.

Note: RMU/t means RMU per tonne.

Table 3-14 (continue): Unit transportation cost between distribution centre *k* and customer zone *l**

Distribution centre	Customer zone (RMU/t)																	
	l_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	l_{10}	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	L_{18}
	For products i_{11}-i_{14}																	
k_1	0	72.82	52.50	11.85	67.74	28.79	16.93	115.17	44.03	108.39	74.52	11.85	38.95	62.66	59.27	44.03	96.54	37.26
k_2	69.04	0	73.86	69.04	128.46	81.89	78.68	110.80	105.98	170.21	20.87	70.65	61.02	126.85	85.10	32.11	67.44	88.31
k_3	74.54	77.92	22.02	50.82	96.56	101.64	64.73	44.04	81.31	132.13	96.56	64.37	33.88	106.72	28.79	52.51	22.02	59.29
k_4	28.74	63.22	57.48	15.32	88.13	59.39	32.57	107.29	63.22	136.03	72.80	22.99	19.16	90.05	49.81	59.39	19.16	44.06
k_5	65.66	131.33	93.57	72.23	0	77.15	50.89	116.56	22.98	41.04	136.26	59.10	73.87	18.05	65.66	90.29	111.63	42.68
k_6	31.07	97.12	91.29	44.67	91.29	0	48.56	165.10	66.04	135.96	89.35	44.67	77.69	77.69	101.00	77.69	145.68	73.81
k_7	20.58	91.67	69.22	26.19	59.87	46.77	0	116.00	31.80	104.77	97.29	9.35	37.42	56.13	52.38	46.77	97.29	22.45
k_8	121.40	124.97	66.05	112.48	126.76	151.75	110.69	0	119.62	153.54	146.40	112.48	82.12	141.04	62.48	89.27	28.56	96.41
k_9	55.75	141.52	81.48	64.32	30.02	72.90	36.45	143.66	0	85.77	145.81	47.17	72.90	32.16	70.76	90.06	113.64	32.16
k_{10}	106.08	175.70	114.37	116.03	41.44	116.03	92.82	142.55	66.30	0	179.02	102.77	116.03	49.72	102.77	132.60	142.55	82.88
k_{11}	74.81	22.10	86.72	66.31	141.13	78.21	88.42	139.43	115.62	183.64	0	78.21	78.21	136.03	103.72	59.51	113.92	102.02
k_{12}	13.58	85.41	50.47	15.53	69.88	44.64	9.70	122.30	42.70	120.36	89.29	0	34.94	69.88	56.29	44.64	100.94	29.11
k_{13}	72.36	70.55	14.47	30.75	81.40	72.36	36.18	83.21	61.50	126.63	81.40	34.37	0	86.83	28.94	19.90	61.50	36.18
k_{14}	72.66	155.15	102.12	82.48	21.60	78.56	58.92	155.15	29.46	58.92	157.12	70.70	94.27	0	92.30	109.98	147.30	58.92
k_{15}	62.62	94.83	19.68	55.47	71.57	93.04	50.10	62.62	59.05	110.94	109.15	51.89	28.63	84.10	0	46.52	50.10	33.99

* There is no difference among several scenarios and time periods.

Note: RMU/t means RMU per tonne.

Inventory

The inventory holding cost is shown in Table 3-15, and it is independent of the product being held, but varies from one location to another. Initial inventories for each product for the manufacturing plants are assumed to be known and at a certain level. This is equal to the maximum production capacity of the plants for a week. Warehouses and distribution centres are assume to hold zero initial inventories.

Two distinct cases are examined with different levels of safety stock held in the system. This is ensured by the values of parameters $\mathrm{n}^{DC}, \mathrm{n}^{W}, \mathrm{n}^{P}$, as provided in Table 3-16. In the first version there are low safety stock requirements, whereas in the second version the needs of safety stock quantities are high.

Table 3-15: Inventory holding cost in plant *j* in warehouse *m* and in distribution centre *k**

Node (RMU/t)			
Plant		**Distribution centre**	
j_1	8.25	k_1	8.25
j_2	8.55	k_2	8.55
j_3	8.98	k_3	8.98
Warehouse		k_4	8.93
m_1	8.25	k_5	8.85
m_2	8.55	k_6	6.90
m_3	8.98	k_7	8.06
m_4	8.93	k_8	6.08
m_5	8.06	k_9	12.00
m_6	10.28	k_{10}	8.85
		k_{11}	8.12
		k_{12}	10.66
		k_{13}	10.28
		k_{14}	8.95
		k_{15}	8.83

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Table 3-16: Inventory requirements in plant *j* , warehouse *m*, and distribution centre *k**

Case	Safety stock held (in number of days equivalent)		
	n^{P}	n^{W}	n^{DC}
Low inventories	1	1	1
High inventories	6	3	2

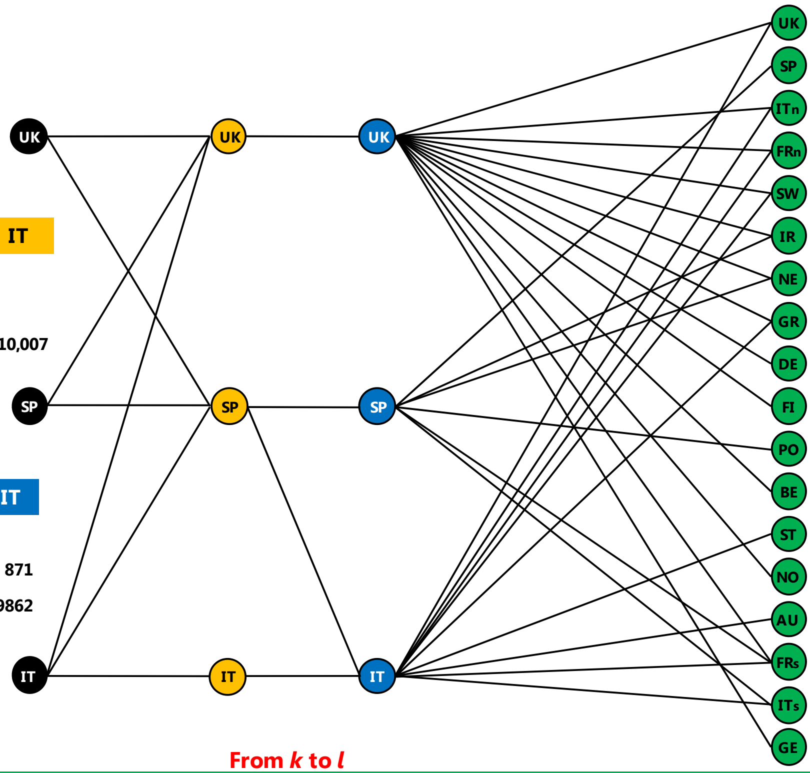
* There is no difference among several scenarios and time periods.

3.4.2 Implementation

The model M1 was solved using ILOG CPLEX 11.2.0 solver incorporated in GAMS 22.9 software (Rosenthal, 2008). The model consisted of 181,104 constraints, 73,692 continuous variables, and 381 discrete variables. A Pentium M, with 1.6 GHz and 512 RAM, was employed for running the model and the solution was reached in 293 CPU seconds with 0% integrality gap.

Results for low inventories case

The optimal SCN structure for this case is shown in Figure 3-4. The SCN consists of three warehouses, placed in United Kingdom, Spain and Italy and three distribution centres located in the same countries. The structure is primarily a result of the demand patterns considered since the three countries which host the manufacturing plants are also the biggest customers. However, since none of the plants can produce the whole range of products, and plant capacity is restricted due to production constraints, all plants provide products to all warehouses.



From *j* to *m*

	UK	SP	IT
UK	29,784	592	
SP	276	16,535	
IT	536	355	10,007

From *m* to *k*

	UK	SP	IT
UK	30,199		
SP		16,385	871
IT			9862

From *k* to *l*

	UK	SP	ITn	FRn	SW	IR	NE	GR	DE	FI	PO	BE	ST	NO	AU	FRs	ITs	GE
UK	15,446		1042	2647	1988	1027	1171	16	743	495		916	394	101		65		3754
SP		13,541				280	864				565					800	116	
IT	65		4364	194	88			958					46		388	680	3843	

Figure 3-4: Optimal SCN from the model M1 for low inventories case

The total expected value of the network's cost comes to 6,031,650 RMU and its breakdown is shown in Table 3-17. Inventories in plants, warehouses, and distribution centres are presented in Figure 3-5 and are reducing with time.

Table 3-17: Optimal cost breakdown from the model M1 for low inventories case

Type of cost	RMU
Fixed infrastructure cost	456,000
Production cost	3,359,600
Material handling cost	515,770
Transportation cost	1,170,700
Inventory cost	529,580
Total optimal cost	6,031,650

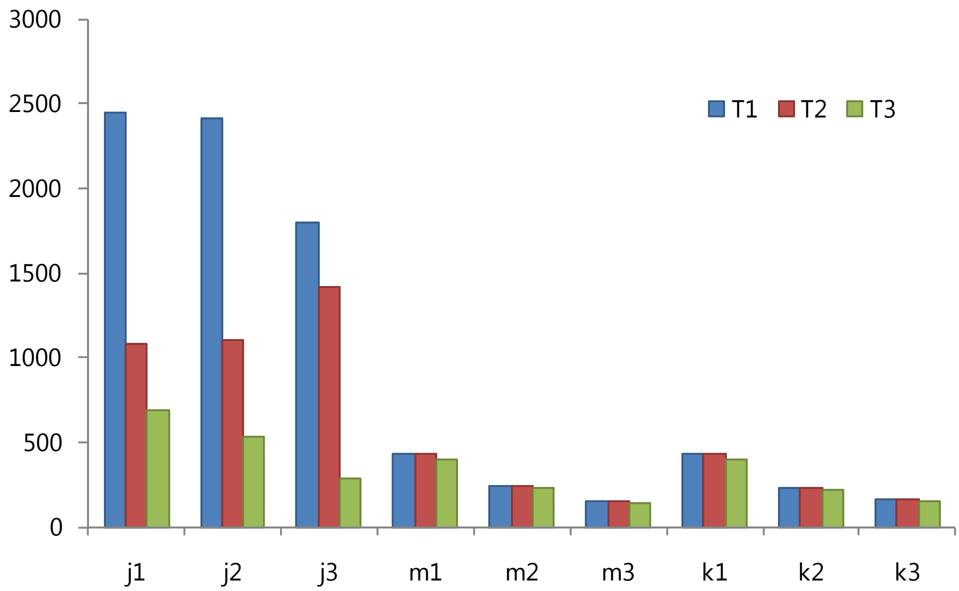
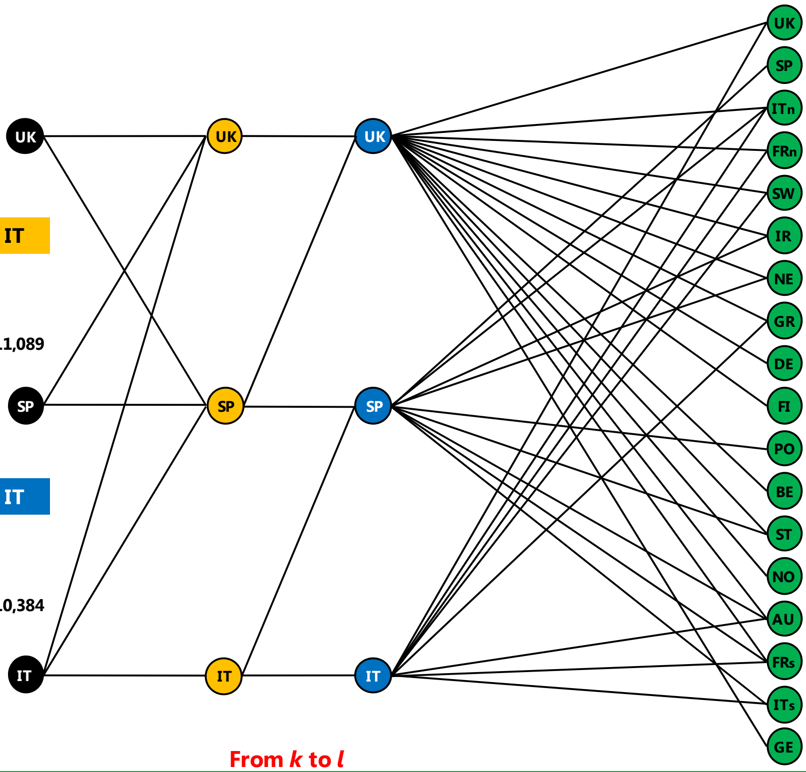


Figure 3-5: Inventory levels in plants, warehouses, and distribution centres (low inventories)

Results for high inventories case

If the network needs to hold higher levels of inventories in order to minimise the probability of not satisfying product demands, the optimal structure changes as shown in Figure 3-6.

Some transportation links between warehouses and distribution centres and between distribution centres and customer zones are modified compared to the low inventories case. More specifically, the warehouse of Spain no longer supplies products to Italy's distribution centre and begun to supply the U.K. distribution centre. Furthermore, Italy's warehouse begun to provide products to Spain's distribution centre. The changes occurred in transportation links between distribution centres and customer zones are mainly concern Spain's distribution centre which started serving the customer zones of North Italy, Switzerland, and Austria. Moreover, the U.K. distribution centre started serving Austria's customer zone whereas Italy's distribution centre interrupted its service to Switzerland's customer zone.



From *j* to *m*

	UK	SP	IT
UK	31,201	585	
SP	69	17,277	
IT	167	2	11,089

From *m* to *k*

	UK	SP	IT
UK	30,250		
SP	31	17,153	
IT		269	10,384

From *k* to *l*

	UK	SP	ITn	FRn	SW	IR	NE	GR	DE	FI	PO	BE	ST	NO	AU	FRs	ITs	GE
UK	15,448		1045	2647	1986	783	1171	4	743	495		910	352	101	30	16		3754
SP		13,541	11			524	864				565		88		163	851	350	
IT	62		4349	194	91			971							144	678	3608	

Figure 3-6: Optimal SCN from the model M1 for high inventories case

The total cost increases to 6,874,790 RMU. As expected all operating costs of the network are increased, as higher volumes of products and inventories have to be produced, transferred and stored (see Table 3-18). Regarding inventories it should be noted that the profile of inventories held in the plants change and tend to increase with time as shown in Figure 3-7.

Table 3-18: Optimal cost breakdown from the model M1 for high inventories case

Type of cost	RMU
Fixed infrastructure cost	456,000
Production cost	3,866,900
Material handling cost	529,800
Transportation cost	1,203,200
Inventory cost	818,890
Total optimal cost	6,874,790

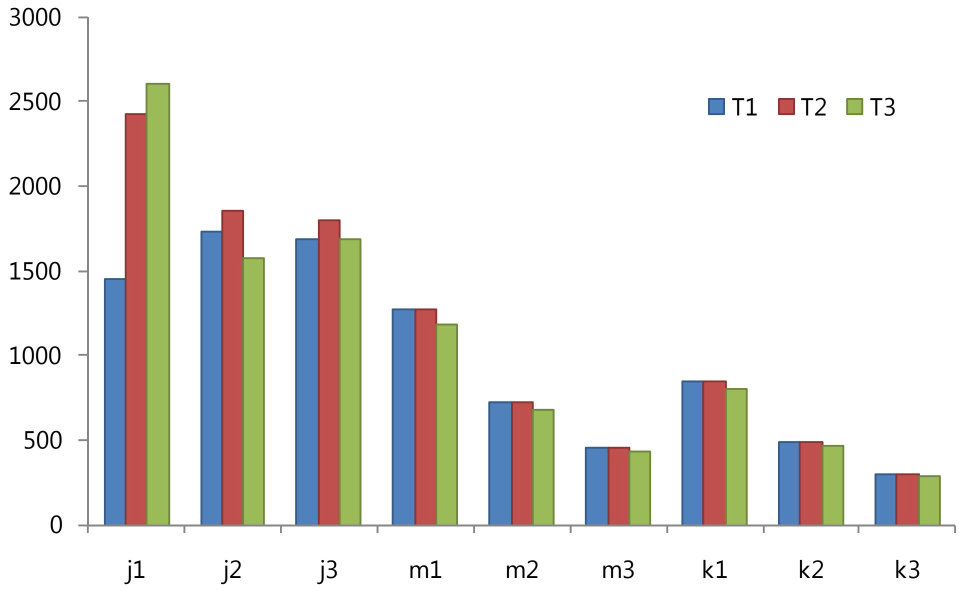


Figure 3-7: Inventory levels in plants, warehouses, and distribution centres (high inventories)

3.4.3 Parameter sensitivity analysis

In this part the performance of the proposed model is tested in several cases by changing some of the parameters, which express the production, distribution, and material handling conditions.

In many business occasions a production decrease is a frequent result of activities such as labour force strikes, equipment accidents and raw materials stock outs. At an aggregate level this potential condition could be expressed by decreasing the maximum production capacity of each plant ($P_{ijt}^{[s],max}$). Figure 3-8 presents the optimal configuration and cost breakdown of the network after a 10% decrease in the maximum production capacity. The optimal network structure in this case results in an additional transportation link between the warehouse of Spain and the U.K. distribution centre, comparing to the base case.

Another interesting business situation that requires further investigation is when the total transportation flow from one node to other must exceed a minimum requirement in order to be placed. In this way fixed costs associated with the establishment of a transportation link (fleet management expenses, cargo handling equipment investments etc.) are covered by the revenues earned from this minimum flow. In the present case study, the zero minimum transportation flow $Q_{mk}^{min} = Q_{kl}^{min} = 0$ in many business cases is unrealistic.

Figure 3-9 illustrates the optimal configuration and cost breakdown of the network when the minimum total transportation flow between a warehouse and a distribution is set to 1000 tonnes/week.

Cost breakdown

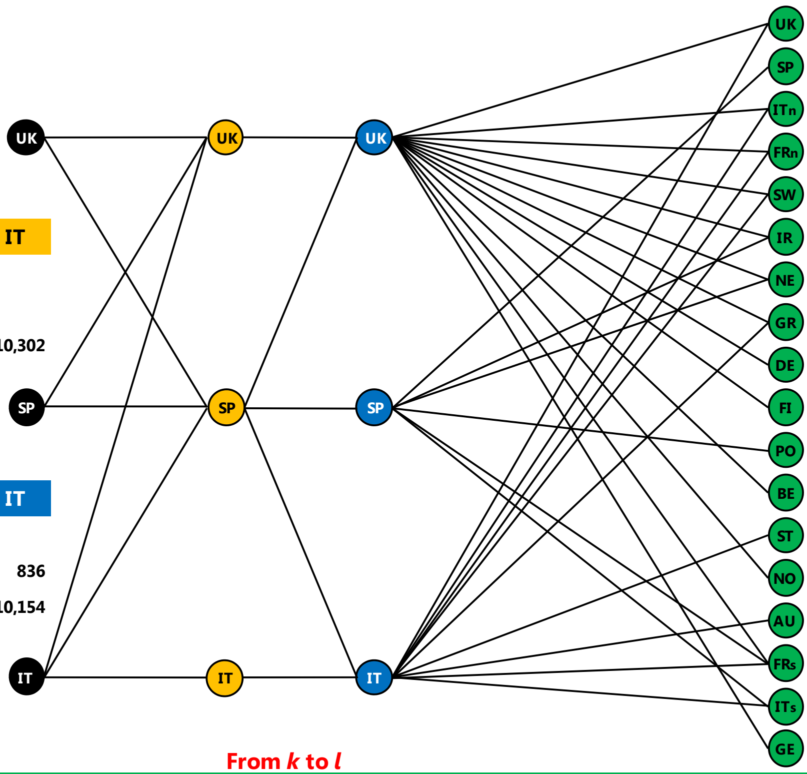
TOTAL	**6,140,390**
Production	3,551,400
Infrastructure	456,000
Material handling	516,280
Transportation	1,166,700
Inventory	450,010

From *j* to *m*

	UK	SP	IT
UK	29,549	726	
SP	168	16,549	
IT	398	395	10,302

From *m* to *k*

	UK	SP	IT
UK	29,724		
SP	22	16,578	836
IT			10,154



From *k* to *l*

	UK	SP	ITn	FRn	SW	IR	NE	GR	DE	FI	PO	BE	ST	NO	AU	FRs	ITs	GE
UK	15,540		741	2647	2040	897	1171	23	743	495		910	334	101		55		3754
SP		13,541				410	864				565					817	157	
IT	70		4665	194	36			951					106		338	673	3801	

Figure 3-8: Optimal SCN from the model M1 with low inventories and -10% in production capacity

The optimal network in this case, comparing to the base case, results in an additional transportation link between UK's plant and the warehouse of Italy and deleted the transportation link between the Spain's warehouse and the distribution centre of Italy. Moreover, the distribution centre of U.K. is now serving the customer zone of Austria while the distribution centre of Spain is serving the customer zones of

Switzerland, and Austria. Finally, the Italy's distribution centre started serving Ireland's and Finland's customer zones.

Cost breakdown

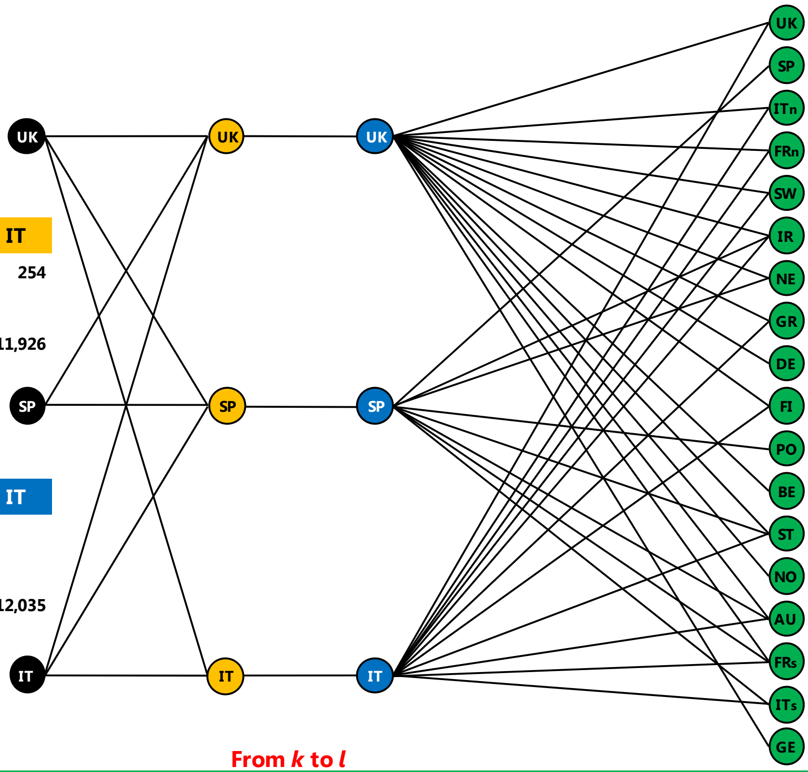
TOTAL	**6,103,060**
Production	3,359,400
Infrastructure	456,000
Material handling	518,090
Transportation	1,231,600
Inventory	537,970

From *j* to *m*

	UK	SP	IT
UK	29,666	1311	254
SP	392	15,317	
IT	179	41	11,926

From *m* to *k*

	UK	SP	IT
UK	28,835		
SP		16,447	
IT			12,035



From *k* to *l*

	UK	SP	ITn	FRn	SW	IR	NE	GR	DE	FI	PO	BE	ST	NO	AU	FRs	ITs	GE
UK	15,437		101	2647	1871	1027	1171	50	743	290		910	285	101	48	55		3754
SP		13,541				272	864				565		139		165	562	114	
IT	73		5305	194	205	8		970		204			16		123	945	3844	

Figure 3-9: Optimal SCN from the model M1 with low inventories and for 1000 t/w min flow

3.5 Concluding remarks

This chapter presented a detailed mathematical formulation for the problem of designing SCNs comprising multiproduct production facilities with shared production resources, warehouses, distribution centres and customer zones and operating under demand uncertainty, while inventory may be kept at different stages in the network. Uncertainty is captured in terms of a number of likely scenarios possible to materialise during the life time of the network. The problem is formulated as MILP and solved to global optimality.

A large-scale European wide distribution network has been used to illustrate the applicability of the developed model. The results obtained provide a good indication of the value of having a model that takes into account the complex interactions that exist in such networks and the effect of inventory levels to the design and operation. The computational cost associated with the problems considered here has been found to be relatively low, thus making the overall model attractive for the solution of large-scale problems.

The proposed MILP model aims to assist senior operations management to take decisions about production allocation, production capacity per site, purchase of raw materials and network configuration taking into account transient demand conditions. The purpose of the model is to be used not as frequent as an Advanced Planning Scheduling (APS) system (daily, weekly or monthly) but for longer periods (such as quarterly, six months or yearly) to address strategic and tactical supply design aspects. Its allocation decisions are set as production targets for the APS systems to optimise production sequences.

CHAPTER 4

Integration of financial statement analysis in the optimal design of SCNs under demand uncertainty

4.1 Introduction

By definition, SCNM concerns a holistic management of all functions taking place and all relations generated in order to begin the product from the source of the raw material and to arrive at the shelf of the sales centres. Consequently, either quantitative or qualitative models that aim to illustrate, improve, and optimise SCN's design and operation should consider functions such as production, distribution, procurement, financial management, marketing, and human resources, just to name a few.

The importance of simultaneously integration of these functions in SCN models has been pointed out in Chapter 1 whereas in the literature presented in Chapter 2 it became clear that the integration of SCN models with financial aspects is limited and focused mainly on scheduling and planning of batch process industries with budgeting and cash flow management being their merely financial considerations.

Physical SCNs are parallel in all firms by financial SCNs involving decisions about capital investments, borrowing, dividends, and other factors under the control of the firm's financial managers. These two SCNs are inextricably linked, especially at the strategic level of planning although their synergy effect is not widely appreciated (Shapiro, 2001). One of the most important responsibilities of the treasurers of different nodes of the SCN is the management of the sources and uses of funds. While making sure that cash is available to meet short-term needs, such as payrolls and invoice payments to the other nodes, treasurers must plan for strategic funds management to facilitate long-term growth via capital expansion or acquisition (Márquez, 2010).

This chapter first and foremost aims to fill a gap in the SCN modelling literature by introducing a mathematical model that integrates financial considerations with SCND decisions under demand uncertainty. The detailed and dynamic SCN design model presented in Chapter 3 is enriched with a mathematical formulation that captures the financial status of the SCN through financial statement analysis and through Economic Value Added (EVA™). The objective of the resulting MILP model is to maximise the company's shareholder value through the operation of its SCN, taking into account several design, operating, and financial constraints.

Section 4.2 presents a justification for the importance of financial management considerations within SCN followed by a mathematical formulation in Section 4.3. The applicability of the developed model is illustrated in Section 4.4 by using a large-scale case study. Finally, concluding remarks are drawn in Section 4.5.

4.2 Financial considerations

4.2.1 Financial statement analysis

Financial operations are supplementary to production operations. They are essential and important activities because they ensure financing of production and distribution operations. Moreover, financing is necessary for investments in new production processes, in new production equipment, and in new innovative products. With the absence of financing, expansion in new emerging markets is hard to accomplish and thus the sustainability and growth of the SCN is jeopardised.

The basic sources of financing are loans and credit lines from financial institutions and funds from shareholders and potential investors, through retention of earnings and increases in equity stocks under either an Initial Public Offering (IPO) or Secondary Equity Offerings (SEO).

In order to attract capitals from these two investment groups, companies should have an unambiguously and satisfactory financial status. The evaluation of a company's investing prospect and credit standing is a process based on static and comparative analysis of financial statements (Horrigan, 1966; Rushinek & Rushinek, 1987). This is because the balance sheet and the income statement contain a huge volume of rather complicated data that are interpreted difficult from potential investors without financial background. In a similar vein, financial statement analysis enables financial institutions to benchmark companies in the same industry with relative measures instead of absolute measures (Horrigan, 1966; Rushinek & Rushinek, 1987).

Financial statements, along with the accompanying footnotes, represent the heart of an annual report by enabling readers to analyse a company's financial performance and health. Financial statements include (Cowen & Hoffer, 1982):

I. The income statement
II. The balance sheet
III. The statement of cash flows
IV. The statement of stockholders' equity

The first two financial statements are the most important in financial analysis. The income statement facilitates the analysis of a company's growth prospects, cost structure, and profitability. Readers can use the income statement to identify the components and sources of profit. While the income statement reports a company's revenues, expenses, and profitability over a specified period of time the balance sheet reports the company's resources (assets) and how those resources were funded (liabilities and shareholders' equity) on a particular date (end of the quarter or fiscal year). The fundamental balance sheet equation in accounting is: Assets = Liabilities + Shareholders' Equity (Feldman & Libman, 2007). Simply put, the balance sheet is a snapshot of a company's categories and amounts of assets employed and the offsetting liabilities incurred to lenders and owners while the income statement displays the revenues recognised for a specific period, and the costs and expenses charged against these revenues (Helfert, 2003).

income statement
for the year ended dd/mm/yyyy

net sales		**1000**
– cost of goods sold	400	
– selling, general & administrative expenses	200	
– depreciation	100	
earnings before interests and taxes		**300**
– interest paid	65	
taxable income		**235**
– taxes	80	
net operating profits after taxes		**155**
Dividends		65
Addition to retained earnings		90

Figure 4-1: A typical income statement

In Figure 4-1 a typical income statement is illustrated. The basic equation that delineates the construction of this statement is that the revenues minus the expenses yield the income. In Figure 4-2 a typical balance sheet is presented. The development of this statement is that the value of the assets owned by a company is equal to the sum of the value of shareholders' equity and the value of debts to third parties. According to the double-entry accounting system, every financial transaction changes the three aforementioned components but the basic equation is always satisfied.[2]

balance sheet

for the year started dd/mm/yyyy

A. fixed assets		**900**	**C. shareholder's equity**		**350**
A.1. tangible assets	800		C.1. contributed capital	350	
A.2. intangible assets	100		C.2. retained earnings	0	
B. current assets		**200**	**D. debt**		**750**
B.1. inventory	200		D.1. short-term liabilities	200	
B.2. accounts receivable	0		D.2. long-term liabilities	550	
B.3. cash	0				
TOTAL ASSETS (A+B)		***1100***	***TOTAL EQUITY & DEBT (C+D)***		***1100***

Figure 4-2: A typical balance sheet

income statement

for the year ended dd/mm/yyyy

net sales		**1000**
– cost of goods sold	400	
– selling, general & administrative expenses	200	
– depreciation	100	
earnings before interests and taxes		**300**
– interest paid	65	
taxable income		**235**
– taxes	80	
net operating profits after taxes		**155**
Dividends		65
Addition to retained earnings		90

balance sheet

for the year ended dd/mm/yyyy

A. fixed assets		**900**	**C. shareholder's equity**		**440**
A.1. tangible assets	800		C.1. contributed capital	350	
A.2. intangible assets	100		C.2. retained earnings	90	
B. current assets		**290**	**D. debt**		**750**
B.1. inventory	200		D.1. short-term liabilities	200	
B.2. accounts receivable	45		D.2. long-term liabilities	550	
B.3. cash	45				
TOTAL ASSETS (A+B)		***1190***	***TOTAL EQUITY & DEBT (C+D)***		***1190***

Figure 4-3: Interaction of income statement & balance sheet

[2] Double-entry accounting is an accounting system that records the two perspectives of every economic event:

1. Its source: Where did funds come from?
2. Its use: How were the funds used?

These two financial statements interact via the transfer of retained earnings form the income statement to the right side of the balance sheet and more specifically to the shareholders' equity. This occurs when the firm retains part of its earnings instead of paying them out as dividends to shareholders. But in order to satisfy the basic equation of the balance sheet (left side equals right) an analogous increase should take place in its left side. One part increases cash and the remaining increases receivable accounts, where this analogy is determined by both market conditions and company's credit policy. Fig. 4-3 presents a typical pair of these statements along with their interaction illustration.

At the end of a fiscal year, the 90 money units of retained earnings, calculated by applying appropriate accounting principles and board of directors decisions, are transferred to the balance sheet. An increase equal to 90 money units takes place in the shareholder's equity while accounts receivables and cash are each one increased at 45 money units.

The information contained in the four basic financial statements is of major significance to various interested parties who regularly need to have relative measures of the company's operating efficiency. Relative is the key word, because the analysis of financial statements is based on the use of ratios or relative values. Ratio analysis involves methods of calculating and interpreting financial ratios to analyse and monitor the firm's performance. The basic inputs to ratio analysis are the firm's income statement and balance sheet (Feldman & Libman, 2007).

Financial ratios are grouped in categories according to their economic role. More specifically, their most commonly classification is the following (Gitman, 2006):

- Liquidity ratios, which measure the ability of the firm to pay its bills over the short run without undue stress.
- Assets management ratios, which measure how efficiently or intensively a firm uses its assets to generate sales.
- Solvency ratios, which measure the firm's long run ability to meet its obligations, or, more generally, its financial leverage.
- Profitability ratios, which measure how efficiently the firm uses its assets and how efficiently the firm manages its operations.

Liquidity ratios

If a company extends credit to a customer or makes a short-term bank loan, is interested to know whether it will be able to receive the cash in the near future or to repay the loan by cash. That is why credit analysts and bankers look at several measures of liquidity. Liquid assets can be converted into cash quickly and cheaply. Consequently liquidity ratios focus on current assets and current (short-term) liabilities. One advantage of looking at current assets and liabilities is that their book value and market values are likely to be similar.[3]

One of the best known and widely used ratios is the Current Ratio which is defined as:

$$\textbf{Current Ratio} = \frac{\text{current assets}}{\text{current liabilities}}$$

Because current assets and liabilities are, in principle, converted to cash over the following twelve months, the Current Ratio is a measure of short-term liquidity.

The least liquid asset included in current assets is inventory. It is also, the one of which the book values are least reliable as measures of market value, because the quality of inventory is not considered. Some of the inventory might latter turn out to be damaged, obsolete, or lost. Furthermore, relative large inventories are often a sign of short-term trouble because this indicates that the firm might have overestimated sales and overbought or overproduced as a result. For this reason the Quick (or Acid-Test) Ratio omits inventory and is defined as:

$$\textbf{Quick Ratio} = \frac{\text{current assets} - \text{inventory}}{\text{short-term liabilities}}$$

A company's most liquid assets are its holdings of cash and marketable securities. That is why analysts and short-term creditors also look at the Cash Ratio which is defined as:

$$\textbf{Cash Ratio} = \frac{\text{cash}}{\text{short-term liabilities}}$$

A low cash ratio may not matter if the firm can borrow on short notice.

Assets management ratios

Financial analysts employ another set of ratios to judge how efficiently the firm is using its assets. The Assets Turnover, or Sales-to-Assets, Ratio shows how hard the firm's assets are being put to use. A high ratio compared with other firms in the same industry could indicate that the firm is working close to capacity. It may prove difficult to generate further business without additional investment. Asset Turnover is defined as:

$$\textbf{Assets Turnover Ratio} = \frac{\text{net sales}}{\text{total assets}}$$

[3] Book values represent the historical cost of the assets when purchased no matter how long ago they were purchased whereas the market values represent how much they worth today.

Instead of looking at the Assets Turnover Ratio, financial managers sometimes look at how hard particular types of capital are being put to use. For example, they might look at the value of sales per dollar invested in fixed assets. Or they might look at the ratio of sales to receivable accounts, or the ratio of sales to inventory. Efficient firms turn over their inventory rapidly and don't tie up more capital than they need in raw materials or finished goods. Fixed Assets Turnover, Receivables Turnover, Inventory Turnover, and are defined as:

$$\textbf{Fixed Assets Turnover Ratio} = \frac{\text{net sales}}{\text{fixed assets}}$$

$$\textbf{Receivables Turnover Ratio} = \frac{\text{net sales}}{\text{accounts receivable}}$$

$$\textbf{Inventory Turnover Ratio} = \frac{\text{cost of goods sold}}{\text{inventory}}$$

Solvency ratios

When a firm borrows money, it promises to make a series of interest payments and then to repay the amount that it has borrowed. If profits rise, the debt holders continue to receive a fixed interest payment, so that all the gains go to the shareholders. Of course, the reverse happens if profits fall. In this case shareholders bear all the damage. If times are sufficiently hard, a firm that has borrowed heavily may not be able to pay its debts. The firm is then bankrupt and shareholders lose their entire investment. Because debt increases returns to shareholders in good times and reduces them in bad times, it is said to create financial leverage. Solvency ratios measure how much financial leverage the firm has taken on.

A commonly used solvency ratio is the Total Debt Ratio, which express the percent of assets that had been financed by external funds. This ratio is defined as

$$\textbf{Total Debt Ratio} = \frac{\text{total assets} - \text{shareholder's equity}}{\text{total assets}}$$

Frequently, financial analysts are more concerned with the firm's long-term debt than its short-term debt, because the shot-term debt will constantly be changing. Also, a firm's short-term debt might be more of a reflection of trade practice than debt management policy. For these reasons, the Long-Term Debt Ratio expresses is more realistic and is defined as:

$$\textbf{Long-Term Debt Ratio} = \frac{\text{long-term liabilities}}{\text{long-term liabilities} + \text{shareholder's equity}}$$

Another way to express leverage is in terms of the company's Debt/Equity Ratio. This ratio illustrates the value of assets provided by third parties for a unit money value provided by shareholders and is defined as:

$$\textbf{Debt/Equity Ratio} = \frac{\text{short-term liabilities + long-term liabilities}}{\text{shareholder's equity}}$$

Times Interest Earned Ratio is a common measure of financial leverage. This ratio shows the extent to which interest is covered by earnings. Banks prefer to lend to firms whose earnings are far in excess of interest payments. Therefore, analysts often calculate this ratio which is defined as:

$$\textbf{Times Interest Earned Ratio} = \frac{\text{earnings before interest and taxes}}{\text{interest paid}}$$

A problem with Times Interest Earned Ratio is that it is based on earnings before interest and taxes, which is not really a measure of cash available to pay interest. The reason is that depreciation, a noncash expense, has been deducted out. Because interest is most definitely a cash outflow (to creditors), one more realistic way to express this is to define the Cash Coverage Ratio as:

$$\textbf{Cash Coverage Ratio} = \frac{\text{earnings before interest and taxes + depreciation}}{\text{interest paid}}$$

Thus, rather than asking whether earnings are sufficient to cover interest payments, it might be more interesting to calculate the extent to which interest is covered by the cash flow from operations.

Profitability ratios

Profitability ratios focus on the firm's earnings. Companies pay a great deal of attention to their Profit Margin Ratio which expresses the amount of money generated for every unit money value of sales and is defined as:

$$\textbf{Profit Margin Ratio} = \frac{\text{net operating profits after taxes}}{\text{net sales}}$$

Managers often measure the performance of a firm by the Return on Assets Ratio (ROA) and the Return on Equity Ratio (ROE) which are defined as:

$$\textbf{Return on Assets Ratio} = \frac{\text{net operating profits after taxes}}{\text{total assets}}$$

$$\textbf{Return on Equity Ratio} = \frac{\text{net operating profits after taxes}}{\text{shareholder's equity}}$$

A high ROA does not always mean that the company could buy the same assets today and get a high return. Nor does a low return imply that the assets could be employed better elsewhere. But it does suggest that the company should ask some searching questions. In a competitive industry firms can expect to earn only their cost of capital. Therefore, a high return on assets is sometimes cited as an indication that the firm is taking advantage of a monopoly position to charge excessive prices. For example, when a public utility commission tries to determine whether a utility is charging a fair price, much of the argument will centre on a comparison between the cost of capital and the return that the utility is earning (its ROA).

4.2.2 Economic value added™

Financial statements produced under provisions of Generally Accepted Accounting Principles (GAAP) report profits intended to tell creditors the amount of earnings and assets available to pay debts under the most pessimistic interpretations. The earnings amounts tell creditors how well protected they are if the company becomes unable to pay its debts. They do not provide investors an impartial assessment of how well the company performed. There are several approaches to modifying reported net income to make it more meaningful. EVA™ is a well-known and widely used approach (Brealey, Myers, & Marcus, 2004; Ross, Westerfield, & Jordan, 2006).

EVA™ is a proprietary measure developed by Joel M. Stern and G. Bennett Stewart III, and marketed through Stern Stewart & Company (Friedlob & Schleifer, 2003). EVA™ calculation formula is defined as:

$$\begin{aligned}\textbf{EVA} &= \text{net operating profits after taxes} - (\text{cost of capital}) \times (\text{total capital invested}) \\ &= \text{net operating profits after taxes} - (\text{WACC}) \times (\text{total debt} + \text{shareholder's equity})\end{aligned}$$

where (WACC) is the Weighted Average Cost of Capital, a percent expressing, in general, the real costs associated with the main sources of capital employed by the company (Ogier, Gugman, & Spicer, 2004).

Since its introduction, EVA™ has received great popularity among financial analysts and practitioners and moreover various companies' surveys reported great improvements by its implementation (Kleiman, 1999; Lovata & Costigan, 2002; Young, 1997). EVA™ is a better measure of a company's success than the net income. When people look at an annual report, they are interested in knowing if the company will increase stockholders' wealth. They are not interested in paper profits measured using GAAP. Investors want to know the company's economic profit. Equity is defined as "property rights," of which there are two basic types in accounting: the equity of creditors (liabilities) and the equity of owners (stockholders' equity). EVA™ is said to measure in real terms the increase in wealth, defined as total equities, including both creditors' equity and stockholders' equity. EVA™ is the statistic stockholders need. When bonus plans use EVA™ rather than ROA to measure the performance of managers, managers pursue activities congruent with the interests of stockholders (Friedlob & Schleifer, 2003).

Because of its widespread application and significant financial impact, EVA™ has recently stimulated the interest of academics specializing in SCN modelling. Although the lion share of SCN design and operation/planning models featuring a cost minimisation objective (Melo et al., 2009; Mula, Peidro, Díaz-Madroñero, & Vicens, 2010), it is argued that sustainable value creation should gradually substitute cost and profit objective functions (Hofmann & Locker, 2009; Klibi et al., 2010).

4.3 Mathematical formulation

4.3.1 Problem description

As in chapter 3, in this chapter the proposed model, which integrates financial statement analysis, considers the design of a multiproduct, four-echelon SCN as shown in Figure 4-4.

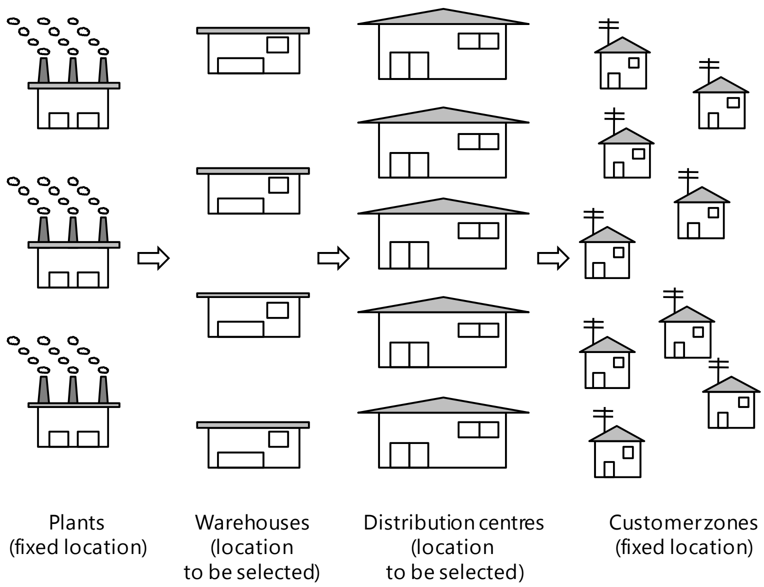


Figure 4-4: The SCN considered in this chapter

The problem under consideration is identical to that presented in Section 3.3.1., where a SCN should be configured in order to satisfy customers' product demand and to comply with several design, operation, and financial constraints. The latter is the feature that distinguishes that model from model M1 presented in Chapter 3. Costs associated with SCN's design and operation cause variations on company's published financial statements and thus should be managed appropriately, in a simultaneous manner with financial operations.

Although the decisions to be determined by the proposed model are the same as those in model M1, the difference lies in the constraints that bound the optimal values of the variables expressing these decisions and also in the objective function being maximised. We repeat these decisions here for case of reference.

Strategic decisions ("here-and-now"):

I. The number, location and capacity of warehouses to be set up
II. The number, location and capacity of distribution centres to be set up
III. The transportation links that need to be established in the network

and tactical ("wait-and-see"):

IV. The flows of materials in the network
V. The production rates at plants
VI. The inventory levels at each warehouse
VII. The inventory levels at each distribution centre

The objective is to find the optimal SCN configuration that maximises the expected value of the company's EVA™, taken over all demand scenarios and during the operation of the network, taking into account several design, operating, and financial constraints.

4.3.2 Mathematical model (M2)

The above problem is formulated through a MILP problem (M2). As in model M1, product demands in model M2 are time-varying and uncertain and thus the dynamic nature is maintained. The scenario approach, as explained in detail in Section 3.2, is employed in handling transient uncertainty, and is shown in Figure 4-5 in order to keep coherency with the case study application that follows on Section 4.4.

The proposed model M2 handles any one of these scenarios, as M1 did, by multiplying each scenario with its probability to occur ψ_s. These probabilities satisfy the condition expressed by constraint (3.1):

$$\sum_{s=1}^{NS} \psi_s = 1 \qquad (3.1)$$

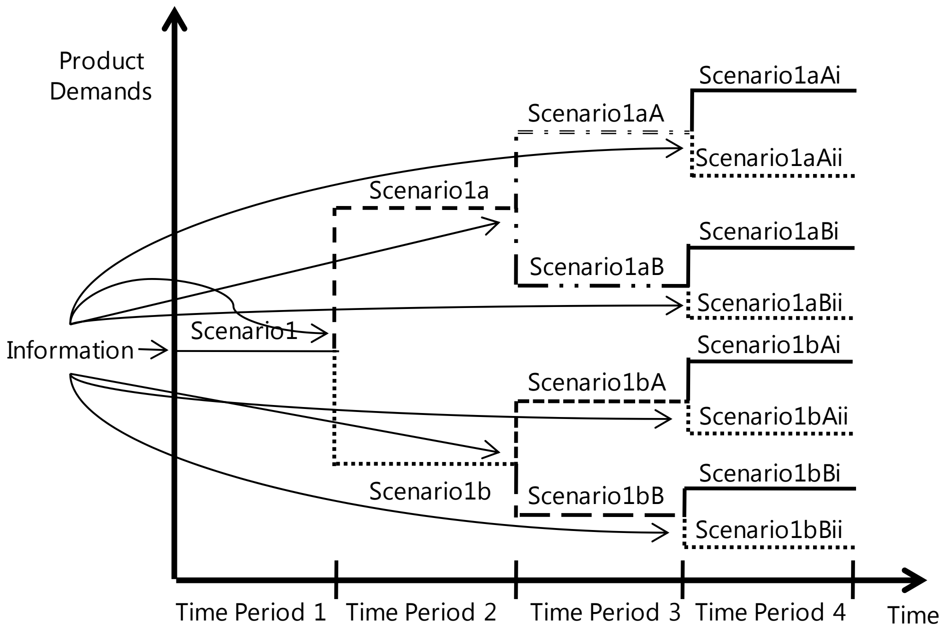


Figure 4-5: Scenarios for problems involving both "here-and-now" and "wait-and-see" decisions

4.3.3 Nomenclature

The nomenclature to be used in this chapter is consistent with that used in Chapter 3, for the model M1. Here we present only those symbols that are different from those listed in Section 3.3.3 and these are either newly introduced or substituting existing ones.

Parameters

C_{ij}^{I}	unit inventory cost of product *i* at plant *j* (substitutes C_{ijt}^{I})
C_{im}^{I}	unit inventory cost of product *i* at warehouse *m* (substitutes C_{imt}^{I})
C_{ik}^{I}	unit inventory cost of product *i* at distribution centre *k* (substitutes C_{ikt}^{I})
CFP_t	percent of net operating profits after taxes that are connected with cash flow at the end of period *t*
CCR_t	minimum bound for Cash Coverage Ratio at the end of time period *t*
CR_t	minimum bound for Cash Ratio at the end of time period *t*
CUR_t	minimum bound for Current Ratio at the end of time period *t*
DCMFM	days corresponded to material flow measurement scale

$\mathrm{DM}_{ilt}^{[s]}$ demand for product *i* from customer zone *l* during time period *t* under scenario *s* (substitutes $\mathrm{D}_{ilt}^{[s]}$)

DER_t upper bound for Debt/Equity ratio at the end of time period *t*

DR_t depreciation rate at the end of time period *t*

FATR_t lower bound for Fixed Assets Turnover Ratio at the end of time period *t*

LTDR_t upper bound for Long-Term Debt Ratio at the end of time period *t*

LTR_t long-term interest rate at the end of time period *t*

PMR_t lower bound for Profit Margin Ratio at the end of time period *t*

$\mathrm{PRICE}_{ilt}^{[s]}$ price of product *i* for customer zone *l* during time period *t* under scenario *s*

Q_{jm}^{min} minimum rate of flow of material that can practically and economically be transferred from plant *j* to warehouse *m*

QR_t lower bound for Quick Ratio at the end of time period *t*

ROAR_t lower bound for Return on Assets Ratio at the end of time period *t*

ROER_t lower bound for Return on Equity Ratio at the end of time period *t*

RTR_t lower bound for Receivables Turnover Ratio at the end of time period *t*

STR_t short-term interest rate at the end of time period *t*

TDR_t upper bound for Total Debt Ratio at the end of time period *t*

TR_t tax rate at the end of time period *t*

WACC_t weighed average cost of all invested capital at the end of time period *t*

Continuous variables

C_t cash at the end of time period *t*

COGS_t cost of goods sold at the end of time period *t*

CA_t current assets at the end of time period *t*

DPR_t depreciation at the end of time period *t*

EBIT_t earning before interests and taxes at the end of time period *t*

E_t equity at the end of time period *t*

FA_t fixed assets at the end of time period *t*

FAI_t fixed assets investment during the time period *t*

HC_t handling cost during the time period *t*

IP_t interest paid at the end of time period *t*

IC_t invested capital at the end of time period *t*

INR_t value of inventory at the end of time period *t*

LTL_t long-term liabilities at the end of time period *t*

NC_t new cash at the end of time period *t*

NIS_t new issued stocks at the end of time period *t*

NSTL_t new short-term liabilities at the end of time period *t*

NRA_t new receivable accounts at the end of time period *t*

NLTL_t new long-term liabilities at the end of time period *t*

NTS_t net sales at the end of time period *t*

NE_t new equity during the time period *t*

NOPAT_t net operating profits after taxes at the end of time period *t*

PC_t production cost during the time period *t*

RA_t receivable accounts at the end of time period *t*

SC_t storage cost during the time period *t*

STL_t short-term liabilities at the end of time period *t*

TI_t taxable income at the end of period *t*

TC_t transportation cost during the time period *t*

4.3.4 Constraints

The basic structural and operational constraints are identical to those presented in Section 3.3.4 for model M1. Here we will present only those constraints that are different from those presented in Section 3.3.4 and these are either newly introduced or substituting existing ones.

Logical constrains for transportation flows

Constraint (4.1) is new and justifies the establishment of the transportation link between a plant *j* and a warehouse *m* in a similar fashion as constraints (3.10) and (3.11) did in Section 3.3.4.2.

$$\sum_i \mathrm{Q}_{ijmt}^{[s]} \geq \mathrm{Q}_{jm}^{min}\mathrm{PW}_m, \forall j, m, t, s = 1, \cdots, \mathrm{NS} \tag{4.1}$$

Safety stock constraints

In constraints (4.2)–(4.4) DCMFM reflects the days included in the scale with which the material flows are measured (e.g. if the material flow is measured in years then the DCMFM will be 365). It substitutes the denominator "7" from constraints (3.25)–(3.27) and thus provides a more generic formulation.

$$\mathrm{I}_{ijt}^{[s],min} = \frac{\mathrm{n}^P}{\mathrm{DCMFM}} \sum_m \mathrm{Q}_{ijmt}^{[s]}, \forall i, j, t, s = 1, \cdots, \mathrm{NS} \tag{4.2}$$

$$\mathrm{I}_{imt}^{[s],min} = \frac{\mathrm{n}^W}{\mathrm{DCMFM}} \sum_k \mathrm{Q}_{imkt}^{[s]}, \forall i, m, t, s = 1, \cdots, \mathrm{NS} \tag{4.3}$$

$$\mathrm{I}_{ikt}^{[s],min} = \frac{\mathrm{n}^{DC}}{\mathrm{DCMFM}} \sum_l \mathrm{Q}_{iklt}^{[s]}, \forall i, j, k, s = 1, \cdots, \mathrm{NS} \tag{4.4}$$

Non-negativity constraints

Constraints (4.5)–(4.64) are new due to the introduction of 27 variables in model M2.

$$\mathrm{C}_t \geq 0, \forall t \tag{4.5}$$

$$\mathrm{COGS}_t \geq 0, \forall t \tag{4.6}$$

$$\mathrm{CA}_t \geq 0, \forall t \tag{4.7}$$

$$\mathrm{DPR}_t \geq 0, \forall t \tag{4.8}$$

$$\mathrm{EBIT}_t \geq 0, \forall t \tag{4.9}$$

$$\mathrm{E}_t \geq 0, \forall t \tag{4.10}$$

$$\mathrm{FA}_t \geq 0, \forall t \tag{4.11}$$

$$\mathrm{FAI}_t \geq 0, \forall t \tag{4.12}$$

$$\mathrm{HC}_t \geq 0, \forall t \tag{4.13}$$

$$\mathrm{IP}_t \geq 0, \forall t \tag{4.14}$$

$$\mathrm{IC}_t \geq 0, \forall t \tag{4.15}$$

$$\mathrm{INR}_t \geq 0, \forall t \tag{4.16}$$

$$\mathrm{LTL}_t \geq 0, \forall t \tag{4.17}$$

$$\mathrm{NC}_t \geq 0, \forall t \tag{4.18}$$

$$\mathrm{NIS}_t \geq 0, \forall t \tag{4.19}$$

$$\mathrm{NSTL}_t \geq 0, \forall t \tag{4.20}$$

$$\mathrm{NRA}_t \geq 0, \forall t \tag{4.21}$$

$$\mathrm{NLTL}_t \geq 0, \forall t \tag{4.22}$$

$$\mathrm{NTS}_t \geq 0, \forall t \tag{4.23}$$

$$\mathrm{NE}_t \geq 0, \forall t \tag{4.24}$$

$$\mathrm{NOPAT}_t \geq 0, \forall t \tag{4.25}$$

$$\mathrm{PC}_t \geq 0, \forall t \tag{4.26}$$

$$\mathrm{RA}_t \geq 0, \forall t \tag{4.27}$$

$$\mathrm{SC}_t \geq 0, \forall t \tag{4.28}$$

$$\mathrm{STL}_t \geq 0, \forall t \tag{4.29}$$

$$\mathrm{TI}_t \geq 0, \forall t \tag{4.30}$$

$$\mathrm{TC}_t \geq 0, \forall t \tag{4.31}$$

Financial operation constraints

The financial cycle of a company is affected by the operations occurred in its SCN. The results of these operations are presented in the income statement and in the balance sheet. Several constraints need to be introduced to model the financial cycle of the company. Starting from the income statement, we define the (NTS_t) which is the expected value, under all product demand scenarios, of the net sales. The following constraint expresses the net sales:

$$\mathrm{NTS}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,l} \mathrm{PRICE}_{ilt}^{[s]} \, \mathrm{DM}_{ilt}^{[s]} \right), \forall t \tag{4.32}$$

The cost of goods sold (COGS_t) constitutes all the expenses realised in order to transform raw materials to products and deliver these products to final customers. In general its constituents are production cost (PC_t), transportation cost (TC_t), materials handling cost (HC_t), and storage cost (SC_t). Constraints (4.33)–(4.37) formulate mathematically all these kinds of costs:

$$\mathrm{COGS}_t = \mathrm{PC}_t + \mathrm{TC}_t + \mathrm{HC}_t + \mathrm{SC}_t, \forall t \tag{4.33}$$

$$\mathrm{PC}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,j} \mathrm{C}_{ij}^{P} \, \mathrm{P}_{ijt}^{[s]} \right), \forall t \tag{4.34}$$

$$\mathrm{TC}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]} + \sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]} + \sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]} \right), \forall t \quad (4.35)$$

$$\mathrm{HC}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,m} \mathrm{C}_{im}^{WH} \left(\sum_j \mathrm{Q}_{ijmt}^{[s]} \right) + \sum_{i,k} \mathrm{C}_{ik}^{DH} \left(\sum_m \mathrm{Q}_{imkt}^{[s]} \right) \right), \forall t \quad (4.36)$$

$$\mathrm{SC}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,j} \mathrm{C}_{ij}^{I} \frac{\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{ij,t-1}^{[s]}}{2} + \sum_{i,m} \mathrm{C}_{im}^{I} \frac{\mathrm{I}_{imt}^{[s]} + \mathrm{I}_{im,t-1}^{[s]}}{2} + \sum_{i,k} \mathrm{C}_{ik}^{I} \frac{\mathrm{I}_{ikt}^{[s]} + \mathrm{I}_{ik,t-1}^{[s]}}{2} \right), \forall t \quad (4.37)$$

Depreciation (DPR_t) is the product of fixed assets (FA) with the depreciation rate (DR). When the cost of goods sold and depreciation are subtracted from the net sales we have earnings before interest and taxes (EBIT_t). Constraints (4.38) and (4.39) express these calculations:

$$\mathrm{DPR}_t = \mathrm{DR}_t \mathrm{FA}_t, \forall t \quad (4.38)$$

$$\mathrm{EBIT}_t = \mathrm{NTS}_t - \mathrm{COGS}_t - \mathrm{DPR}_t, \forall t \quad (4.39)$$

Companies pay interests for both long-term and short-term financing of their operations. The first interest is the product of short-term liabilities (STL_t) with the short-term interest rate (STR_t) while the second is the product of long-term liabilities (LTL_t) with the long-term interest rate (LTR_t). When the sum of these two expenses is subtracted from EBIT_t we have the taxable income (TI_t). This quantity is multiplied with the tax rate (TR_t) and their product is subtracted from the taxable income yielding the net operating profits after taxes (NOPAT_t). Constraints (4.40)–(4.42) formulate these calculations:

$$\mathrm{IP}_t = \mathrm{LTR}_t \mathrm{LTL}_t + \mathrm{STR}_t \mathrm{STL}_t, \forall t \quad (4.40)$$

$$\mathrm{TI}_t = \mathrm{EBIT}_t - \mathrm{IP}_t, \forall t \quad (4.41)$$

$$\mathrm{NOPAT}_t = (1 - \mathrm{TR}_t)\mathrm{TI}_t, \forall t \quad (4.42)$$

NOPAT are the final result of the company's operation and should be presented in its balance sheet in order to inform investors. According to the double-entry accounting system the equity and the cash and/or receivables accounts of the company are increased in a value equal to NOPAT. The money value of NOPAT is not entirely reflected by cash but a part may be accounts receivable. This is known from the company's credit policy to customers. Constraints (4.43)–(4.45) formulate these double entry transactions:

$$\mathrm{NE}_t = \mathrm{NOPAT}_t, \forall t \quad (4.43)$$

$$\mathrm{NC}_t = \mathrm{CFP}_t \mathrm{NOPAT}_t, \forall t \quad (4.44)$$

$$\mathrm{NRA}_t = (1 - \mathrm{CFP}_t)\mathrm{NOPAT}_t, \forall t \tag{4.45}$$

Constraint (4.43) creates a new equity (NE_t) that is equal to NOPAT. Constraint (4.44) states that new cash (NC_t) is generated through one part of the NOPAT whereas constraint (4.45) states that the remaining part generates new receivable accounts (NRA_t). In these two constraints cash flow percent (CFP_t) determines the quantity of each part.

As previously mentioned the basic equation of the balance sheet is the equality of its assets to its debts and equity. Fixed assets (FA_t) and current assets (CA_t) constitute the assets while short-term liabilities (STL_t) and long-term liabilities (LTL_t) constitute the debts. This leads to the following constraint:

$$\mathrm{FA}_t + \mathrm{CA}_t = \mathrm{E}_t + \mathrm{STL}_t + \mathrm{LTL}_t, \forall t \tag{4.46}$$

The current assets represent the most liquid assets of a company and include cash (C_t), accounts receivables (RA_t), and inventory (INR_t).

$$\mathrm{CA}_t = \mathrm{C}_t + \mathrm{RA}_t + \mathrm{INR}_t, \forall t \tag{4.47}$$

Each account included in the balance sheet is changing during a fiscal year due to financial operations. Regarding fixed assets, the establishment of warehouses and distributions centres increases the money value of this account, through fixed assets investment ($\mathrm{FAI_t}$), as shown in constraints (4.48) and (4.49).

$$\mathrm{FA}_t = \mathrm{FA}_{t-1} + \mathrm{FAI}_t, \forall t \tag{4.48}$$

$$\mathrm{FAI}_t = \sum_m \mathrm{C}_m^W \, \mathrm{PW}_m + \sum_k \mathrm{C}_k^D \mathrm{PDC}_k \, , \forall t \tag{4.49}$$

Constraints (4.50)–(4.53) formulate how new cash (NC_t), new receivable accounts (NRA), new short-term liabilities (NSTL_t), and new long-term liabilities (NLTL_t) change their corresponding accounts.

$$\mathrm{C_t} = \mathrm{C}_{t-1} + \mathrm{NC}_t, \forall t \tag{4.50}$$

$$\mathrm{RA}_t = \mathrm{RA}_{t-1} + \mathrm{NRA}_t, \forall t \tag{4.51}$$

$$\mathrm{STL}_t = \mathrm{STL}_{t-1} + \mathrm{NSTL}_t, \forall t \tag{4.52}$$

$$\mathrm{LTL}_t = \mathrm{LTL}_{t-1} + \mathrm{NLTL}_t, \forall t \tag{4.53}$$

The networks' inventory value (INR_t) in each time period under all demand scenarios is measured based on the GAAP of historic cost. This means that its value is based on the lowest price and not on market price. This is the production price. Constraint (4.54) illustrates this valuation:

$$\mathrm{INR}_t = \sum_{s=1}^{NS} \psi_s \left(\sum_{i,j,m,k} \mathrm{C}_{ij}^{P} \left(\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{imt}^{[s]} + \mathrm{I}_{ikt}^{[s]} \right) \right), \forall t \tag{4.54}$$

Except from new equity (NE_t) by NOPAT a company can earn funds by issuing new stocks in the market (NIS_t). This leads to the constraint:

$$\mathrm{E}_t = \mathrm{E}_{t-1} + \mathrm{NE}_t + \mathrm{NIS}_t, \forall t \tag{4.55}$$

Finally the total invested capital (IC_t) in the company is given by the following constraint:

$$\mathrm{IC}_t = \mathrm{E}_t + \mathrm{STL}_t + \mathrm{LTL}_t, \forall t \tag{4.56}$$

Financial ratios constraints

In Section 4.2.1 we provide a throughout presentation of the financial ratios and became clear that these are grouped in four categories according to their economic role. The proposed model incorporates several financial ratios from all the four categories.

The liquidity ratios used in this model are the Current Ratio (CUR_t), the Quick Ratio (QR_t), and the Cash Ratio (CR_t) defined by constraints (4.57), (4.58), and (4.59), respectively. The asset management ratios used in this model are the Fixed Assets Turnover Ratio (FATR_t), expressed by constraint (4.60), and the Receivables Turnover Ratio (RTR_t), expressed by constraint (4.61). Total Debt Ratio (TDR_t), Debt/Equity Ratio (DER_t), Long-Term Debt Ratio (LTDR_t), and Cash Coverage Ratio (CCR_t) are the solvency ratios used in the model and are expressed by constraints (4.62), (4.63), (4.64), and (4.65), respectively. Finally, Profit Margin Ratio (PMR_t), defined by constraint (4.66), Return on Assets Ratio (ROAR_t), defined by constraint (4.67), and Return on Assets Ratio (ROER_t), defined by constraint (4.68), are the profitability ratios employed in the model. The following 12 constraints present the final form of financial ratios employed in our model:

$$\frac{\mathrm{CA}_t}{\mathrm{STL}_t} \geq \mathrm{CUR}_t, \forall t \tag{4.57}$$

$$\frac{\mathrm{CA}_t - \mathrm{INR}_t}{\mathrm{STL}_t} \geq \mathrm{QR}_t, \forall t \tag{4.58}$$

$$\frac{\mathrm{C}_t}{\mathrm{STL}_t} \geq \mathrm{CR}_t, \forall t \tag{4.59}$$

$$\frac{\mathrm{NTS}_t}{\mathrm{FA}_t} \geq \mathrm{FATR}_t, \forall t \tag{4.60}$$

$$\frac{\mathrm{NTS}_t}{\mathrm{RA}_t} \geq \mathrm{RTR}_t, \forall t \tag{4.61}$$

$$\frac{\mathrm{STL}_t + \mathrm{LTL}_t}{\mathrm{FA}_t + \mathrm{CA}_t} \leq \mathrm{TDR}_t, \forall t \tag{4.62}$$

$$\frac{\mathrm{STL}_t + \mathrm{LTL}_t}{\mathrm{E}_t} \leq \mathrm{DER}_t, \forall t \tag{4.63}$$

$$\frac{\mathrm{LTL}_t}{\mathrm{LTL}_t + \mathrm{E}_t} \leq \mathrm{LTDR}_t, \forall t \tag{4.64}$$

$$\frac{\mathrm{EBIT}_t + \mathrm{DPR}_t}{\mathrm{IP}_t} \geq \mathrm{CCR}_t, \forall t \tag{4.65}$$

$$\frac{\mathrm{NOPAT}_t}{\mathrm{NTS}_t} \geq \mathrm{PMR}_t, \forall t \tag{4.66}$$

$$\frac{\mathrm{NOPAT}_t}{\mathrm{FA}_t + \mathrm{CA}_t} \geq \mathrm{ROAR}_t, \forall t \tag{4.67}$$

$$\frac{\mathrm{NOPAT}_t}{\mathrm{E}_t} \geq \mathrm{ROER}_t, \forall t \tag{4.68}$$

For each one of the previous ratios, except the three first solvency ratios expressed by constraints (4.62)–(4.64), a lower bound is defined by the company aiming to guarantee a minimum acceptable value for these ratios or to set a target value. For the three first solvency ratios an upper bound is imposed, for the same purposes.

4.3.5 Objective function

The objective of the optimisation problem is to maximise, for a planning period, the expected value of the company's EVA™, the most contemporary index that evaluates the financial performance of a company. This is because it considers the cost of all capitals invested in the company instead of capitals from third parties. More details about this figure have been presented in Section 4.2.2. In model M2, EVA™ is formulated as follows:

$$\mathrm{OBJ}^2\text{: max} \sum_t (\mathrm{NOPAT}_t - \mathrm{WACC}_t \mathrm{IC}_t)$$

where WACC_t is the weighted average cost of capital that express, in general, the opportunity cost of all capitals invested in the company.

4.3.6 Solution approach

The optimisation problem described by the above objective function OBJ^2 and constraints (3.1)–(3.24), (3.28)–(3.36), and (4.1)–(4.68) is a MILP problem and is solved using standard branch-and-bound techniques.

It should be pointed out that although production and distribution aspects in the SCN design problem could be decomposed into sub-models (e.g. a model for each echelon in the SC) the integration of financial aspects seems to significantly limit potential decomposition opportunities as financial operations are modelled centrally and cannot applied separately. For example the investing and borrowing needs of the company are not managed for each plant, warehouse, distribution but centrally for the own company.

4.4 A case study

4.4.1 Background

The applicability of the proposed MILP model M2 is illustrated through its implementation in the same industrial company presented in Chapter 3. However, the size of the problem is not the same, as in Section 3.4.1, and the data are not identical. In many cases the nodes of the SCN either fixed (plant and customer zones) or potential (warehouses and distribution centres) are not the same as in those in Section 3.4.1. For this reason we will provide all data although some of them are repeated.

The planning horizon of interest is comprised of four one-year time periods. We consider a European wide SCN comprising of three plants serving customers located in eight different countries, as shown in Figure 4-6. A set of four candidate warehouses and six candidate distributions centres is considered for establishment, in order to service the whole market.

For confidentiality reasons the locations of plants, warehouses, distribution centres, and customer zones are referred with numbers and for the financial data the relative money units have substitute the real currency units.

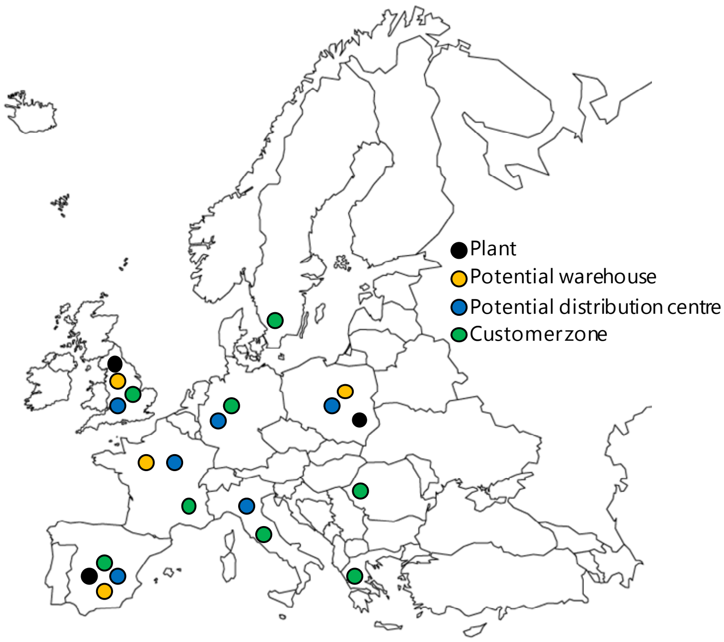


Figure 4-6: The case study SCN

Plants

Each plant produces several products from a portfolio of seven different products using three share production resources and subjected to a maximum production capacity. Table 4-1 presents the utilization of these share manufacturing resources along with the total resource availability, while the maximum production capacity of each plant is provided in Table 4-2. The minimum production capacity is assumed to be zero. The minimum rate of flow of material that can practically and economically be transferred to each warehouse is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Table 4-1: Utilization & availability of resource *e* for product *i* in plant *j**

Plant	Shared resource utilization coefficient ρ_{ije} (h/t)							R_{je} (h/y)
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	
$j_1 \cdot e_1$	0.2381				0.7936			120
$j_1 \cdot e_2$		0.0463	0.0617	0.0694				105
$j_1 \cdot e_3$							0.1634	105
$j_2 \cdot e_1$	0.2178		0.3742					105
$j_2 \cdot e_2$				0.0793	0.1054	0.1582	0.1582	105
$j_2 \cdot e_3$		0.0740	0.1000					105
$j_3 \cdot e_1$			0.1976	0.2222				120
$j_3 \cdot e_2$					0.7789	0.3968	0.3968	165
$j_3 \cdot e_3$	0.1200	0.1543						120

* There is no difference among several scenarios and time periods.
Note: h/t means hours per tonne and h/y means hours per year.

Table 4-2: Maximum production capacity of plant *j* for product *i**

Plant	Product (t/y)						
	i_1	i_2	i_3	i_4	i_5	i_6	i_7
j_1	158	2268	1701	1512	0	812	642
j_2	0	1411	1058	1328	996	664	664
j_3	972	778	607	540	0	416	416

* There is no difference among several scenarios and time periods.
Note: t/y means tonnes per year.

Table 4-3: Unit production and unit inventory holding cost of product *i* in plan *j**

Plant	Production (RMU/t)		Inventory (RMU/t)	
	i_1-i_6	i_7	i_1-i_6	i_7
j_1	61.27	256.90	8.25	8.25
j_2	59.45	268.50	8.55	8.55
j_3	61.44	270.80	8.98	8.98

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Each plant generates costs because of production, storage, and transportation of products to warehouses. Table 4-3 presents the unit production and storage cost in each plant, whereas Table 4-4 provides the unit transportation cost from plants to potential warehouses. In each plant and for each product there are initial inventories, equal to maximum production capacity of the plant. For every plant a safety stock requirement is set equal to 15 day's material flow.

Table 4-4: Unit transportation cost between plant *j* and warehouse *m**

Plant	Warehouse (RMU/t)			
	m_1	m_2	m_3	m_4
	For products i_1-i_6			
j_1	1.24	58.56	62.30	26.16
j_2	60.82	1.68	70.96	43.93
j_3	76.16	79.21	1.52	54.83
	For product i_7			
j_1	1.35	63.46	67.51	28.35
j_2	82.70	2.29	96.48	59.72
j_3	94.90	98.69	1.80	68.32

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Warehouses

The establishment of a warehouse imposes an infrastructure cost. Moreover, the operation of the warehouse is associated with material handling costs and storage costs. Details on these costs are presented in Table 4-5. All warehouses are assumed to have a maximum and a minimum material handling capacity of 14,000 tonnes per year and zero, respectively. The coefficient relating the capacity of a warehouse to the throughput of each material handled is taken to be unity ($\gamma_{im} = 1$).

Table 4-5: Infrastructure, material handling, & inventory holding costs of warehouse *m**

Warehouse	Infrastructure (C_m^W) (RMU/y)	Material handling (C_{im}^{WH}) (RMU/t)	Inventory holding (C_{ij}^I) (RMU/t)
m_1	10,000	4.25	8.25
m_2	5000	4.55	8.55
m_3	4000	4.98	8.98
m_4	6000	4.93	8.93

* There is no difference among several scenarios and time periods.
Note: RMU/y means RMU per year and RMU/t means RMU per tonne.

Table 4-6 presents the unit transportation cost from potential warehouses to distribution centres. Warehouses hold no initial inventory and the safety stock requirement is set equal to 15 day's material flow. The minimum rate of flow of material that can practically and economically be transferred to each distribution centre is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Table 4-6: Unit transportation cost between warehouse *m* and distribution centre *k**

Warehouse	Distribution centre (RMU/t)					
	k_1	k_2	k_3	k_4	k_5	k_6
	For products i_1-i_6					
m_1	0	74.40	76.13	25.96	69.21	29.41
m_2	58.85	0	62.96	45.16	109.49	39.80
m_3	72.83	76.14	0	49.66	94.35	99.32
m_4	28.54	62.78	57.08	0	87.52	58.98
	For product i_7					
m_1	0	75.28	77.03	26.26	70.02	29.76
m_2	60.87	0	65.12	46.71	113.25	42.20
m_3	90.75	94.88	0	61.88	117.57	123.76
m_4	28.88	63.54	57.77	0	88.58	59.69

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Distribution centres

The establishment of a distribution centre requires an infrastructure cost. Moreover, the operation of the distribution centre is associated with material handling costs and storage costs. Details on these costs are presented in Table 4-7. All distribution centres are assumed to have a maximum and a minimum material handling capacity of 7000 tonnes per year and zero, respectively. The coefficient relating the capacity of a warehouse to the throughput of each material handled is taken to be unity ($\gamma_{ik} = 1$). Table 4-8 presents the unit transportation costs from potential distribution centres to each customer zone. Distribution centres hold no initial inventory and the safety stock requirement is set equal to 15 day's material flow. The minimum rate of flow of material that can practically and economically be transferred to each customer zone is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Table 4-7: Infrastructure, material handling, & inventory holding costs of distribution centre *k**

Distribution centre	Infrastructure (C_k^D) (RMU/y)	Material handling (C_{ik}^{DH}) (RMU/t)	Inventory holding (C_{ik}^{I}) (RMU/t)
k_1	10,000	4.25	8.25
k_2	5000	4.55	8.55
k_3	4000	4.98	8.98
k_4	6000	4.93	8.93
k_5	6500	4.85	8.85
k_6	4000	3.90	6.90

* There is no difference among several scenarios and time periods.
Note: RMU/w means RMU per year and RMU/t means RMU per tonne.

Table 4-8: Unit transportation cost between distribution centre *k* and customer zone *l**

Distribution centre	Customer zone (RMU/t)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
	For products i_1-i_6							
k_1	0	75.61	54.51	12.30	70.34	29.89	17.58	119.57
k_2	73.55	0	78.68	73.55	136.84	87.23	83.81	118.02
k_3	73.28	76.71	19.96	49.96	94.93	99.93	63.28	83.80
k_4	26.58	58.47	53.16	3.29	81.51	54.93	30.12	79.23
k_5	77.16	154.33	109.96	84.88	7.15	90.67	59.80	136.97
k_6	27.08	84.65	79.57	38.93	79.57	17.42	42.32	143.90
	For product i_7							
k_1	0	73.12	52.71	11.90	68.02	28.90	17.00	115.63
k_2	73.20	0	78.12	73.20	136.20	86.82	83.42	117.47
k_3	81.65	85.36	24.96	55.67	105.78	111.34	70.52	88.25
k_4	24.76	54.48	49.53	3.89	75.95	51.18	28.06	72.46
k_5	77.52	155.04	110.47	85.27	7.98	91.09	60.08	137.60
k_6	32.65	102.06	95.93	46.94	95.93	18.06	51.03	173.50

* There is no difference among several scenarios and time periods.
Note: RMU/t means RMU per tonne.

Customer zones

For the fist time period product demands for the eight customer zones are given in Table 4-9. In the next time period uncertainty is becoming more discernible so two predictions are made, as shown in Tables 4-10 and 4-11. In a similar manner, in the third time period two predictions are made for each one of the previous' period demand predictions and are illustrated in Tables 4-12 to 4-15. Finally, each of the demand predictions for the third period leads to two distinct demand predictions for the fourth time period, as presented in Tables 4-16 to 4-23. Overall, we consider eight distinct scenarios organised in an analogous tree structure of the type shown in Figure 4-5. All scenarios are assumed to have an equal probability to occur.

Table 4-9: Demand for product *i* from customer zone *l* over the first period (all scenarios)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	50	0	0	115	0	0	0	0
i_2	0	53	105	0	0	0	155	0
i_3	187	115	0	307	310	0	0	0
i_4	0	103	115	0	0	0	205	192
i_5	0	76	0	0	0	0	0	0
i_6	100	0	95	0	0	354	0	194
i_7	0	30	89	80	0	0	0	0

Note: t/y means tonnes per year.

Table 4-10: Demand for product *i* from customer zone *l* over the second period (scenario 1-4)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	75	0	0	173	0	0	0	0
i_2	0	80	158	0	0	0	233	0
i_3	281	173	0	461	465	0	0	0
i_4	0	155	173	0	0	0	308	288
i_5	0	114	0	0	0	0	0	0
i_6	150	0	143	0	0	531	0	291
i_7	0	45	134	120	0	0	0	0

Note: t/y means tonnes per year.

Table 4-11: Demand for product *i* from customer zone *l* over the second period (scenario 5-8)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	25	0	0	58	0	0	0	0
i_2	0	27	53	0	0	0	78	0
i_3	94	58	0	154	155	0	0	0
i_4	0	52	58	0	0	0	103	96
i_5	0	38	0	0	0	0	0	0
i_6	50	0	48	0	0	177	0	97
i_7	0	15	45	40	0	0	0	0

Note: t/y means tonnes per year.

Table 4-12: Demand for product *i* from customer zone *l* over the third period (scenario 1-2)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	94	0	0	216	0	0	0	0
i_2	0	100	198	0	0	0	291	0
i_3	351	216	0	576	581	0	0	0
i_4	0	194	216	0	0	0	385	360
i_5	0	143	0	0	0	0	0	0
i_6	188	0	179	0	0	664	0	364
i_7	0	56	168	150	0	0	0	0

Note: t/y means tonnes per year.

Table 4-13: Demand for product *i* from customer zone *l* over the third period (scenario 3-4)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	56	0	0	130	0	0	0	0
i_2	0	60	119	0	0	0	175	0
i_3	211	130	0	346	349	0	0	0
i_4	0	116	130	0	0	0	231	216
i_5	0	86	0	0	0	0	0	0
i_6	113	0	107	0	0	398	0	218
i_7	0	34	101	90	0	0	0	0

Note: t/y means tonnes per year.

Table 4-14: Demand for product *i* from customer zone *l* over the third period (scenario 5-6)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	31	0	0	73	0	0	0	0
i_2	0	34	66	0	0	0	98	0
i_3	118	73	0	193	194	0	0	0
i_4	0	65	73	0	0	0	129	120
i_5	0	48	0	0	0	0	0	0
i_6	63	0	60	0	0	221	0	121
i_7	0	19	56	50	0	0	0	0

Note: t/y means tonnes per year.

Table 4-15: Demand for product *i* from customer zone *l* over the third period (scenario 7-8)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	19	0	0	44	0	0	0	0
i_2	0	20	40	0	0	0	59	0
i_3	71	44	0	116	116	0	0	0
i_4	0	39	44	0	0	0	77	72
i_5	0	29	0	0	0	0	0	0
i_6	38	0	36	0	0	133	0	73
i_7	0	11	34	30	0	0	0	0

Note: t/y means tonnes per year.

Table 4-16: Demand for product *i* from customer zone *l* over the fourth period (scenario 1)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	103	0	0	238	0	0	0	0
i_2	0	110	218	0	0	0	320	0
i_3	386	238	0	634	639	0	0	0
i_4	0	213	238	0	0	0	424	396
i_5	0	157	0	0	0	0	0	0
i_6	207	0	197	0	0	730	0	400
i_7	0	62	185	165	0	0	0	0

Note: t/y means tonnes per year.

Table 4-17: Demand for product *i* from customer zone *l* over the fourth period (scenario 2)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	85	0	0	194	0	0	0	0
i_2	0	90	178	0	0	0	262	0
i_3	316	194	0	518	523	0	0	0
i_4	0	175	194	0	0	0	347	324
i_5	0	129	0	0	0	0	0	0
i_6	169	0	161	0	0	598	0	328
i_7	0	50	151	135	0	0	0	0

Note: t/y means tonnes per year.

Table 4-18: Demand for product *i* from customer zone *l* over the fourth period (scenario 3)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	62	0	0	143	0	0	0	0
i_2	0	66	131	0	0	0	193	0
i_3	232	143	0	381	384	0	0	0
i_4	0	128	143	0	0	0	254	238
i_5	0	95	0	0	0	0	0	0
i_6	124	0	118	0	0	438	0	240
i_7	0	37	111	99	0	0	0	0

Note: t/y means tonnes per year.

Table 4-19: Demand for product *i* from customer zone *l* over the fourth period (scenario 4)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	50	0	0	117	0	0	0	0
i_2	0	54	107	0	0	0	158	0
i_3	190	117	0	311	314	0	0	0
i_4	0	104	117	0	0	0	208	194
i_5	0	77	0	0	0	0	0	0
i_6	102	0	96	0	0	358	0	196
i_7	0	31	91	81	0	0	0	0

Note: t/y means tonnes per year.

Table 4-20: Demand for product i from customer zone l over the fourth period (scenario 5)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	34	0	0	80	0	0	0	0
i_2	0	37	73	0	0	0	108	0
i_3	130	80	0	212	213	0	0	0
i_4	0	72	80	0	0	0	142	132
i_5	0	53	0	0	0	0	0	0
i_6	69	0	66	0	0	243	0	133
i_7	0	21	62	55	0	0	0	0

Note: t/y means tonnes per year.

Table 4-21: Demand for product i from customer zone l over the fourth period (scenario 6)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	28	0	0	66	0	0	0	0
i_2	0	31	59	0	0	0	88	0
i_3	106	66	0	174	175	0	0	0
i_4	0	59	66	0	0	0	116	108
i_5	0	43	0	0	0	0	0	0
i_6	57	0	54	0	0	199	0	109
i_7	0	17	50	45	0	0	0	0

Note: t/y means tonnes per year.

Table 4-22: Demand for product i from customer zone l over the fourth period (scenario 7)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	21	0	0	48	0	0	0	0
i_2	0	22	44	0	0	0	65	0
i_3	78	48	0	128	128	0	0	0
i_4	0	43	48	0	0	0	85	79
i_5	0	32	0	0	0	0	0	0
i_6	42	0	40	0	0	146	0	80
i_7	0	12	37	33	0	0	0	0

Note: t/y means tonnes per year.

Table 4-23: Demand for product *i* from customer zone *l* over the fourth period (scenario 8)

Product	Customer zone (t/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	17	0	0	40	0	0	0	0
i_2	0	18	36	0	0	0	53	0
i_3	64	40	0	104	104	0	0	0
i_4	0	35	40	0	0	0	69	65
i_5	0	26	0	0	0	0	0	0
i_6	34	0	32	0	0	120	0	66
i_7	0	10	31	27	0	0	0	0

Note: t/y means tonnes per year.

The pricing policy is a source for a competitive advantage. The scope of the pricing policy is to position the products in markets with a price which the customer evaluates as fair. Usually, this price is higher than the cost of the product and allows the creation of a specified profit. Different customers, with different preferences, with different hierarchy of their needs, and from different geographical regions, are willing to pay different prices for the same product.

In this case study, price diversification is based only on geographical segmentation. In other words, for each time period the company defines a price for each product, for each customer zone. Tables 4-24 to 4-27 present these prices.

Table 4-24: Price for product *i* from customer zone *l* over the first period*

Product	Customer zone (RMU/t)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	750	0	0	740	0	0	0	0
i_2	0	740	730	0	0	0	770	0
i_3	1040	1030	0	710	750	0	0	0
i_4	0	1010	1150	0	0	0	1100	990
i_5	0	690	0	0	0	0	0	0
i_6	1160	0	1250	0	0	1220	0	1350
i_7	0	1350	1340	1330	0	0	0	0

* There is no difference among several scenarios.
Note: RMU/t means RMU per tonne.

Table 4-25: Price for product *i* from customer zone *l* over the second period*

Product	Customer zone (RMU/t)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	788	0	0	777	0	0	0	0
i_2	0	777	767	0	0	0	809	0
i_3	1092	1082	0	746	788	0	0	0
i_4	0	1061	1208	0	0	0	1155	1040
i_5	0	725	0	0	0	0	0	0
i_6	1218	0	1313	0	0	1281	0	1418
i_7	0	1418	1407	1397	0	0	0	0

* There is no difference among several scenarios.
Note: RMU/t means RMU per tonne.

Table 4-26: Price for product *i* from customer zone *l* over the third period*

Customer zone	Product demand (RMU/t)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	827	0	0	816	0	0	0	0
i_2	0	816	805	0	0	0	849	0
i_3	1147	1136	0	783	827	0	0	0
i_4	0	1114	1268	0	0	0	1213	1092
i_5	0	761	0	0	0	0	0	0
i_6	1279	0	1379	0	0	1345	0	1489
i_7	0	1489	1477	1467	0	0	0	0

* There is no difference among several scenarios.
Note: RMU/t means RMU per tonne.

Table 4-27: Price for product *i* from customer zone *l* over the third period*

Product	Customer zone (RMU/t)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	868	0	0	857	0	0	0	0
i_2	0	857	845	0	0	0	891	0
i_3	1204	1193	0	822	868	0	0	0
i_4	0	1170	1331	0	0	0	1274	1147
i_5	0	799	0	0	0	0	0	0
i_6	1343	0	1448	0	0	1412	0	1563
i_7	0	1563	1551	1540	0	0	0	0

* There is no difference among several scenarios.
Note: RMU/t means RMU per tonne.

Financial operation

At the beginning of the planning horizon the case study company has a balance sheet shown in Table 4-28. The financial operation parameters are given in Table 4-29 whereas the targeted financial ratios in Table 4-30 (see constraints (4.88)–(4.93)).

Table 4-28: Balance sheet at the beginning of planning period

Account	RMU	Account	RMU
Fixed assets	**500,000**	**Equity**	**1,129,088**
Tangible assets	500,000	Contributed capital	1,129,088
Intangible assets	0	Retained earnings	0
Current assets	**1,979,088**	**Debt**	**1,350,000**
Inventory	550,000	Short-term liabilities	450,000
Accounts receivable	50,000	Long-term liabilities	900,000
Cash	1,379,088		
TOTAL ASSETS	***2,479,088***	***TOTAL EQUITY & DEBT***	***2,479,088***

Table 4-29: Financial cycle parameters for period *t**

Financial parameter	Time period			
	t_1	t_2	t_3	t_4
Depreciation rate (DR_t)	0.250	0.250	0.250	0.250
Short-term interest rate (STR_t)	0.035	0.040	0.045	0.050
Long-term interest rate (LTR_t)	0.070	0.075	0.080	0.085
Tax rate (TR_t)	0.200	0.225	0.250	0.275
Coefficient connecting profits to cash (CFP_t)	0.600	0.600	0.600	0.600
Weighted average cost of capital (WACC_t)	0.015	0.020	0.025	0.030

* There is no difference among several scenarios.

Table 4-30: Bounds for financial ratios*

Financial ratio	Target	Direction
Current Ratio(CUR_t)	2.000	Higher than
Quick Ratio,QR_t)	1.250	Higher than
Cash Ratio (CR_t)	1.000	Higher than
Fixed Assets Turnover Ratio (FATR_t)	1.100	Higher than
Receivables Turnover Ratio (RTR_t)	1.670	Higher than
Total Debt Ratio (TDR_t)	0.600	Lower than
Debt/Equity Ratio (DER_t)	1.500	Lower than
Long Term Debt Ratio (LTDR_t)	0.800	Lower than
Cash Coverage Ratio (CCR_t)	5.000	Higher than
Profit Margin Ratio (PMR_t)	0.050	Higher than
Return on Assets Ratio (ROAR_t)	0.010	Higher than
Return on Equity Ratio (ROER_t)	0.020	Higher than

* There is no difference among several scenarios and time periods.

4.4.2 Implementation

The model M2 was solved using ILOG CPLEX 11.2.0 solver incorporated in GAMS 22.9 software (Rosenthal, 2008). The model consisted of 44,020 constrains, 23,766 continuous variables, and 82 discrete variables. A Pentium M, with 1.6 GHz, was employed for running the model and the solution was reached in 193 CPU seconds with 0% integrality gap.

Results

Figure 4-7 illustrates the optimal configuration of the network from the model M2. The optimal network structure is consisted of four warehouses and three distribution centres. The total created economic added value is 1,756,627 RMU. The total cost related to non financial operations is 3,954,301 RMU and the transportation cost is its major contributor with 67% share whereas the inventory cost is its minor contributor with 2%. All plants supply products to all warehouses. The distribution centres selected are three. The first which is supplied only from the fourth warehouse and the second and fifth which are supplied from all warehouses. Finally, each customer zone is supplied by only one distribution centre.

Inventories in plants, warehouses, and distribution centres are presented in Figure 4-8. It is noted that inventories in plants are very high in contrast to inventories held in warehouses and in distribution centres. As previously mentioned, for the first time period inventories in plants are equal to the maximum production capacity of each plant. For the next time periods inventory levels are decided from the model and as shown in Figure 4-7 are decreasing in the first plant whereas are increasing in the other two plants. Inventories in warehouses and distribution centres although kept at low levels are presenting an increasing trend.

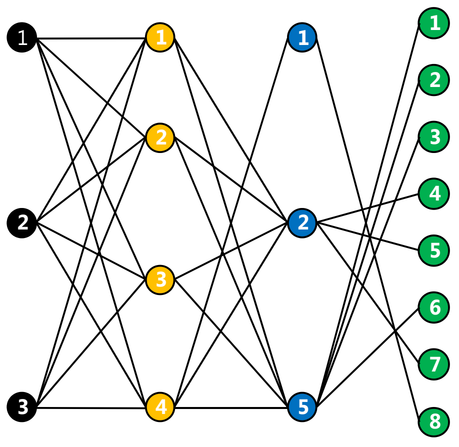
Economic Value Added	**1,756,627**	
Total production cost	919,976	23%
Total handling cost	117,674	3%
Total transportation cost	2,658,482	67%
Total infrastructure cost	186,000	5%
Total inventory cost	72,169	2%
Total cost	**3,954,301**	

From *j* to *m*

	1	2	3	4
1	1685	971	1678	1784
2	481	1038	523	1383
3	419	744	945	1019

From *m* to *k*

	1	2	5
1		1211	1349
2		876	1818
3		1819	1263
4	1576	893	1608



From *k* to *l*

	1	2	3	4	5	6	7	8
1								1544
2				2018	1239		1443	
5	1351	1516	1630			1416		

Figure 4-7: Optimal SCN from model M2

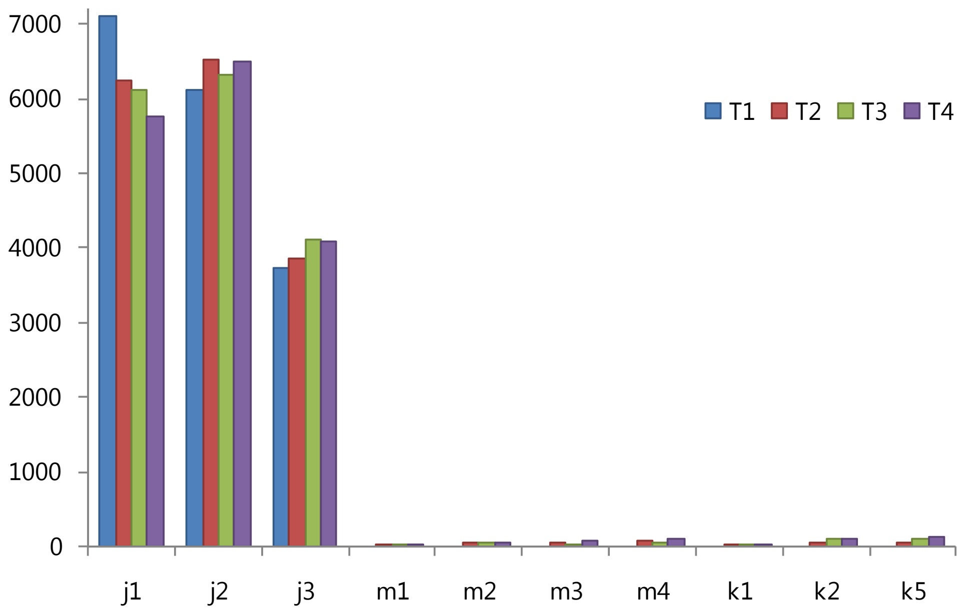


Figure 4-8: Inventory levels in plants, warehouses, and distribution centres (M2 model)

4.4.3 Financial sensitivity analysis

In this section the performance of the proposed model M2 is tested in several cases by changing some of the parameters, which express the economic environment. These parameters are important because the company has no semantic province on them and in many cases are accepted as conditions. However, companies could make realistic and accurate estimations about these parameters by employing advanced forecasting techniques and also various financial products enable them to hedge against uncertainties on these important parameters. The information from this analysis enables SC managers to assess how the network will change in cases of economic activity deviations.

One important financial parameter is the WACC. This parameter expresses the cost of all invested capitals, either loans or equity. Although the company could affect the cost of loans, the cost of equity is based on financial market conditions. Another important financial parameter is the percent of net operating profit after taxes NOPAT that is reflected by cash (CFP). Although a company affects this percent through its credit policy this impact is not unique. Market conditions define which will be this percent. Tax rate is also an important financial parameter that affects a company's wealth. Companies could affect the tax rate percent by "lobbying" on government regulation or by "triangle pricing" through off-shore companies but these cases are not common. Finally, long-term (LTR) and short-term (STR) interest rates are totally defined by credit markets.

Table 4-31 presents the reaction of the proposed model to various changes in these parameters ranging from -10% to +10%. Changes in the WACC, LTR and STR change only the EVA™ but not the configuration of the network whereas changes in CFP and TAXRATE alter the configuration of the network, as shown in Table 4-31.

Table 4-31: Financial sensitivity analysis on model M1

Parameter	Change	EVA	Configuration/Flows
CFP	-10%	-36.49%	PL_j to PW_m where j=1,2,3 and m=1,2,3. PW_m to PDC_k where (m,k)=(1,2), (2,5), (3,2), (3,5), (3,6). PDC_k to CZ_l where (k,l)=(2,5), (2,7), (5,1), (5,2), (5,3), (5,4), (5,6), (6,8).
	-5%	-19.35%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,5), (3,2), (3,5), (4,5). PDC_k to CZ_l where (k,l)=(2,5), (5,1), (5,2), (5,3), (5,4), (5,6), (5,7), (5,8).
	-2%	-8.08%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,2), (2,5), (3,2), (3,5), (4,5). PDC_k to CZ_l where (k,l)=(2,5), (2,6), (5,1), (5,2), (5,3), (5,4), (5,7), (5,8).
	-1%	-4.17%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,3), (1,5), (1,6), (2,2), (2,5), (3,2), (4,2), (4,5). PDC_k to CZ_l where (k,l)=(2,4), (2,5), (2,7), (3,6), (5,1), (5,2), (5,3), (6,8).
	1%	3.95%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,3), (2,5), (2,6), (3,3), (3,5), (3,6), (4,2), (4,3), (4,4), (4,6). PDC_k to CZ_l where (k,l)=(2,5), (3,7), (3,8), (4,2), (5,1), (5,6), (6,3), (6,4).
	2%	8.28%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,1), (2,2), (2,5), (3,1), (3,2), (3,5), (4,1), (4,2), (4,3), (4,5). PDC_k to CZ_l where (k,l)=(1,5), (2,1), (2,4), (2,7), (3,3), (5,2), (5,3), (5,8).
	5%	22.01%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,3), (1,5), (2,4), (3,1), (3,3), (4,1), (3,3). PDC_k to CZ_l where (k,l)=(1,1), (1,7), (3,6), (4,3), (4,5), (5,2), (5,4), (5,8).
	10%	49.45%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,1), (1,2), (1,4), (1,5), (1,6), (2,2), (2,3), (2,4), (3,1), (3,4), (3,6), (4,1), (4,4). PDC_k to CZ_l where (k,l)=(1,3), (1,6), (2,8), (3,2), (4,4), (4,7), (5,5), (6,1).
TAXRATE	-10%	-0.01%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,5), (3,2), (3,5), (4,2), (4,5). PDC_k to CZ_l where (k,l)=(2,5), (2,6), (5,1), (5,2), (5,3), (5,4), (5,7), (5,8).
	-5%	0.02%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,4), (1,5), (2,5), (3,5), (4,5). PDC_k to CZ_l where (k,l)=(4,5), (5,1), (5,2), (5,3), (5,4), (5,6), (5,7), (5,8).
	-2%	-0.12%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,3), (1,5), (2,1), (2,5), (3,2), (3,3), (3,5), (4,1), (4,2), (4,3), (4,5). PDC_k to CZ_l where (k,l)=(1,2), (2,3), (2,4), (3,1), (3,5), (5,6), (5,7), (5,8).
	-1%	0.00%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (2,2), (2,3), (2,5), (3,2), (3,5), (4,2), (4,5). PDC_k to CZ_l where (k,l)=(2,4), (2,5), (2,6), (3,1), (5,2), (5,3), (5,7), (5,8).
	1%	-0.19%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,3), (1,5), (1,6), (2,3), (2,5), (3,3), (3,5), (3,6), (4,3), (4,5), (4,6). PDC_k to CZ_l where (k,l)=(3,5), (3,6), (5,1), (5,2), (5,4), (5,7), (6,3), (6,8).
	2%	-0.08%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,2), (1,5), (1,6), (2,2), (2,5), (2,6), (3,3), (3,5), (3,6), (4,2), (4,5), (4,6). PDC_k to CZ_l where (k,l)=(2,5), (2,8), (3,3), (5,1), (5,2), (5,7), (6,4), (6,6).
	5%	-0.09%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,5), (1,6), (2,1), (2,5), (3,1), (3,2), (3,6), (4,2), (4,5). PDC_k to CZ_l where (k,l)=(1,6), (2,5), (2,7), (5,1), (5,2), (5,4), (6,3), (6,8).
	10%	-0.45%	PL_j to PW_m where j=1,2,3 and m=1,2,3,4. PW_m to PDC_k where (m,k)=(1,5), (1,6), (2,6), (3,5), (3,6), (4,2), (4,5), (4,6). PDC_k to CZ_l where (k,l)=(2,4), (2,7), (5,1), (5,3), (5,5), (5,6), (6,2), (6,8).

Regarding the selected warehouses, only in the case of a 10% decrease in the CFP the fourth warehouse is not selected. In all the other cases the three plants supply products to all four possible warehouses but the total amount of flow transported from each plant to each warehouse for the planning period and under all scenarios is changing.

Regarding the selected distribution centres, we can see that while CFP is decreasing the transportation connections from warehouses to distribution centres are decreasing and thus the network is less complicated. On the other had, increases in CFP are force the network to be more complicated by establishing new transportation connections. In the case of TAXRATE deviations we cannot trace any underlying pattern regarding the transportation connections from warehouses to distribution centres. The total amount of flow transported from each warehouse to each distribution centre for the planning period and under all scenarios is changing in all the cases reported in Table 4-31.

Finally, in all cases the customer zones are supplied by only one distribution centre and also the total amount of flow transported to each customer zone is not changing. The only change that occurs is which distribution centre supplies a customer zone. For this reason the complexity of the network is only affected by the transportation connections established between warehouses and distribution centres.

4.4.4 Comparison with a non financial model

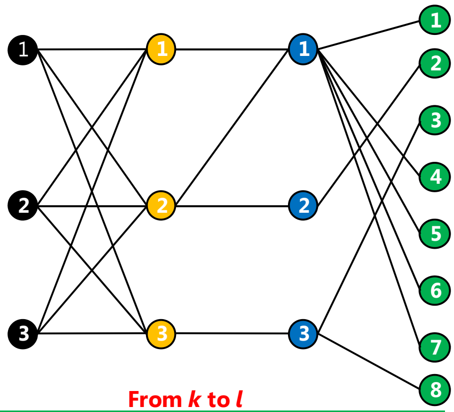
Integration of financial statement analysis is the main novelty of our model M2. Hence, it is deemed worthy to evaluate its benefit by comparing the results of our proposed model M2 with a model (M2′) that ignores financial statement analysis. Both models have the same objective function (EVA™ maximisation) but the model M2′ ignores constraints (4.57)–(4.68). In specific we solve again the MILP problem M2′ consisted of objective function OBJ^2 and constraints (3.1)–(3.24), (3.28)–(3.36), and (4.1)–(4.56), using the real case study data presented in Section 4.4.

Figure 4-9 illustrates the optimal configuration of the network from model M2′. This SCN is less complicated because it does not select the fourth warehouse and also selects the three distribution centres that are closed to the three warehouses. It decreases the number of transportation links and simultaneously it increases the flow between warehouses and distribution centres. This configuration is driven by the minor transportation cost between these nodes and is reflected in the transportation cost figure of model M2′ which is almost 20% of the transportation cost of model M2. Moreover, the total network cost of model M2′ is almost 50% of that of model M2. Again, each customer zone is supplied by only one distribution centre. Regarding inventories in various nodes of the SCN the picture is the same with that of model M2, as shown in Figure 4-9.

Economic Value Added	**534,988**	
Total production cost	904,092	50%
Total handling cost	110,894	6%
Total transportation cost	562,665	31%
Total infrastructure cost	152,000	9%
Total inventory cost	72,169	4%
Total cost	**1,801,820**	

From *j* to *m*

	1	2	3
1	6116	400	400
2	400	1468	400
3	400	400	2439



From *m* to *k*

	1	2	3
1	6851		
2	693	1538	
3			3207

From *k* to *l*

	1	2	3	4	5	6	7	8
1	1351			2018	1239	1416	1443	
2		1516						
3			1630					1544

Figure 4-9: Optimal SCN from model M2′

The advantage of model M2′ over model M2, in total cost, is not reflected in the EVA™ where model M2 creates triple value for shareholders compared to that created by model M2′. The main reason for this is the financial operation of a company. EVA™ is affected by the net operating profits after taxes (NOPAT) and by total invested capital (IC). Regarding IC, both models have almost the same value in this account. Concerning NOPAT, this account is created by substituting various financial expenses from net sales (NTS) and both models have the same NTS because this variable is totally driven by customer demands (see constraints (3.15) and (4.32)). Additionally, the invested capital (IC) is affected by company's decisions to finance its operations by three different, in terms of cost, financing modes. Thus various non effective financial decisions from the NFM explain this phenomenon.

NOPAT is created by substituting various financial expenses from net sales (NTS) and both models have the same NTS because this variable is totally driven by customer demands. As the operational costs are lower for the model M2′ one should expect to see this superiority in the EVA™. However the vital difference between the two models lies in financing. Model M2, forced mainly by solvency ratios, selects to finance its operations with equity whereas model M2′ with leverage. The latter has a significant cost known as interest while the former has no cost. This deduction from model's M2′ NOPAT results in almost one third of model's M2 EVA™.

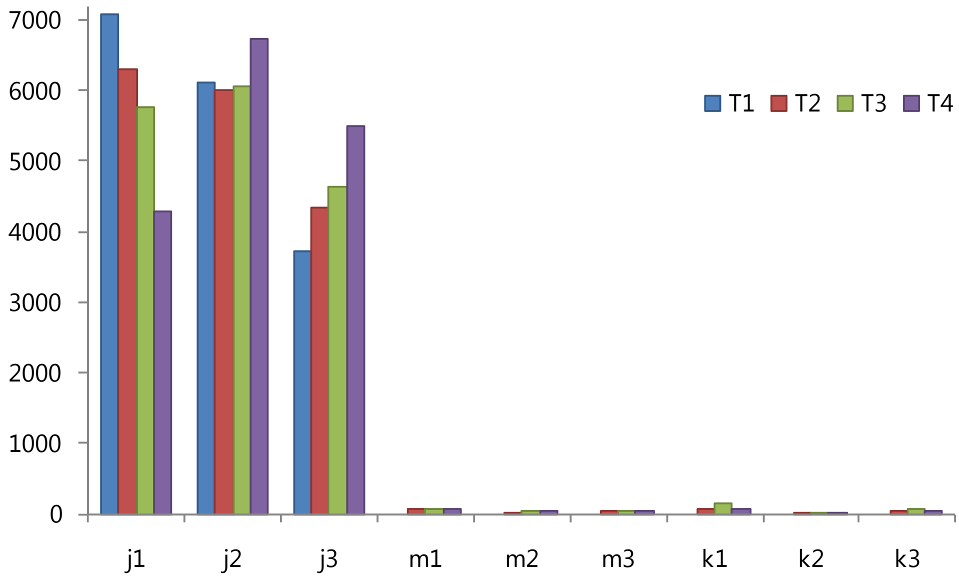


Figure 4-10: Inventory levels in plants, warehouses, and distribution centres (M2′ model)

A more illustrative explanation of model's M2′ superiority is shown in Figures 4-11 to 4-14. Figure 4-11 shows how liquidity ratios are formulated for both models at each time period and it is evident that model M2 is performing much better than model M2′ in all individual ratios. In assets management ratios, shown in Figure 4-12, model M2′ is performing slightly better than model M2. In solvency ratios, shown in Figure 4-13, the main drawback of model M2′ is evident. Model M2′ decides to finance its operations with external funds from capital markets and financial institutions (almost 90% of its IC) and increases substantially its liabilities and its paid interest. In contrast, model M2 due to financial constraints imposed in its financial operation takes into account the cost of high liabilities and only 10% of its IC comes from capital markets and financial institutions. Figure 4-14 shows the trade-off between the models. The profitability ratio Return on Equity (ROE) is extremely high for model M2′ in contrast to model's M2 corresponding ratio for all time periods. Although, ROE is a popular ratio for investment decisions, because it expresses a convenient percent that investors could compare to other alternative investment products, a holistic evaluation of company's financial status is required in cases of effective financial decisions. Speculation and other strategies that do not express the median investor are out of the scope of our model.

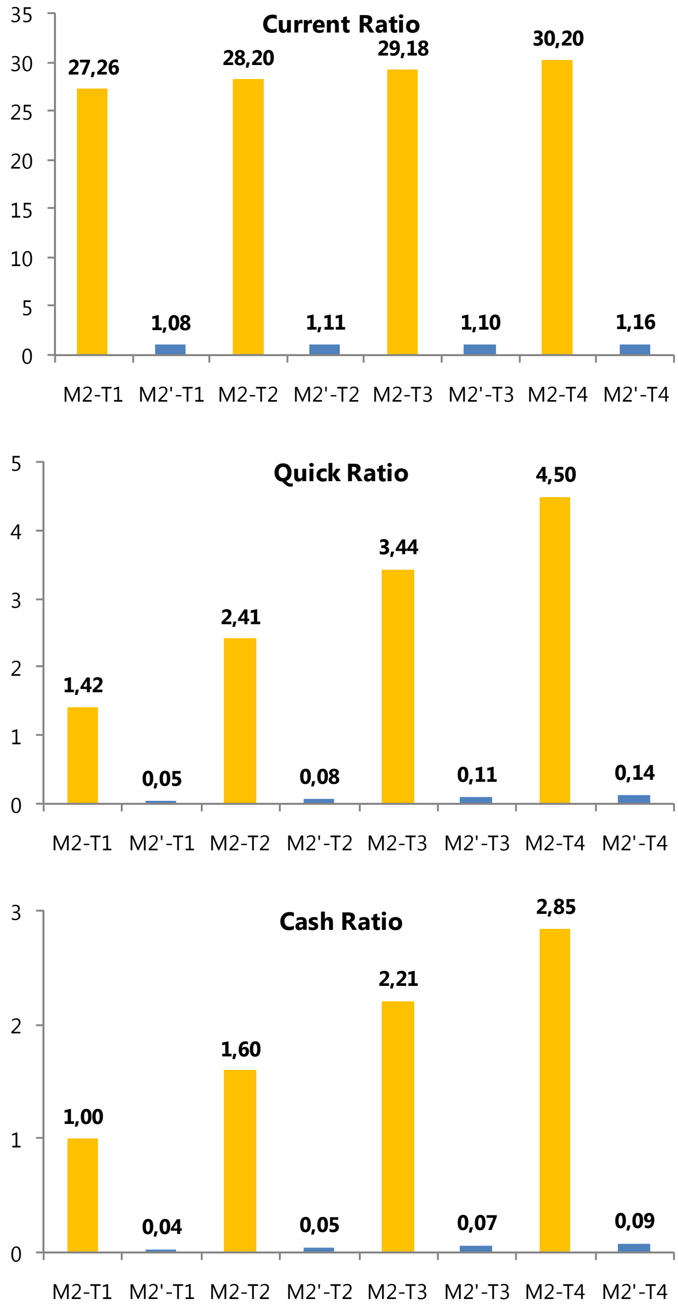


Figure 4-11: Liquidity ratios of models M2 and M2′ at each time period

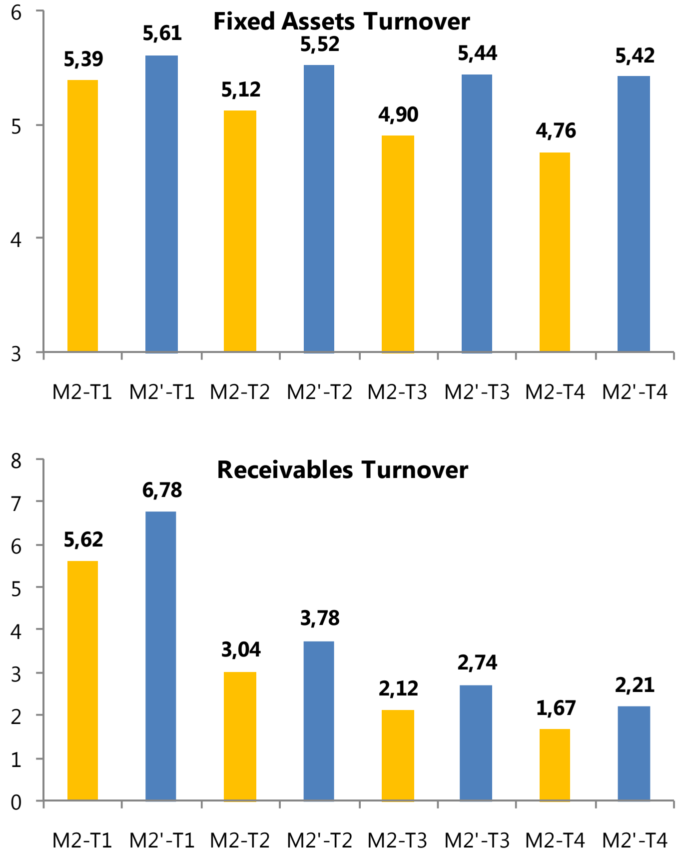


Figure 4-12: Assets management ratios of models M2 and M2′ at each time period

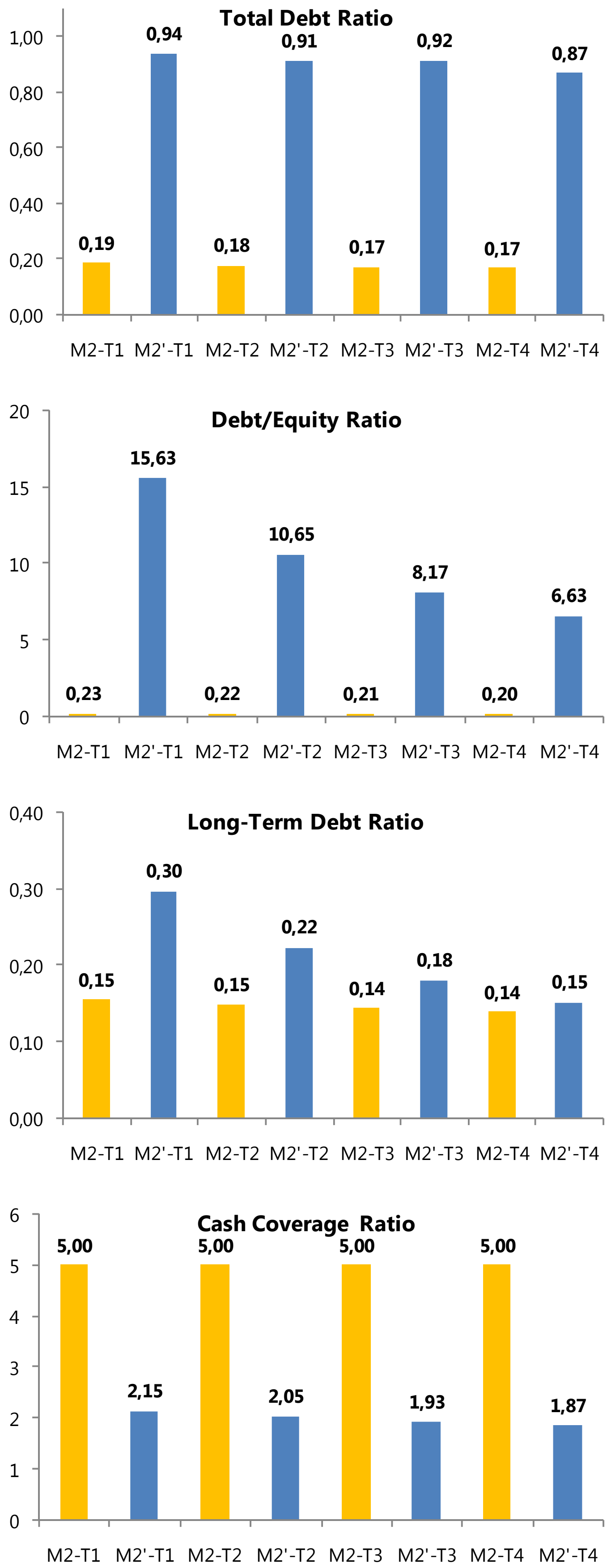


Figure 4-13: Solvency ratios of models M2 and M2′ at each time period

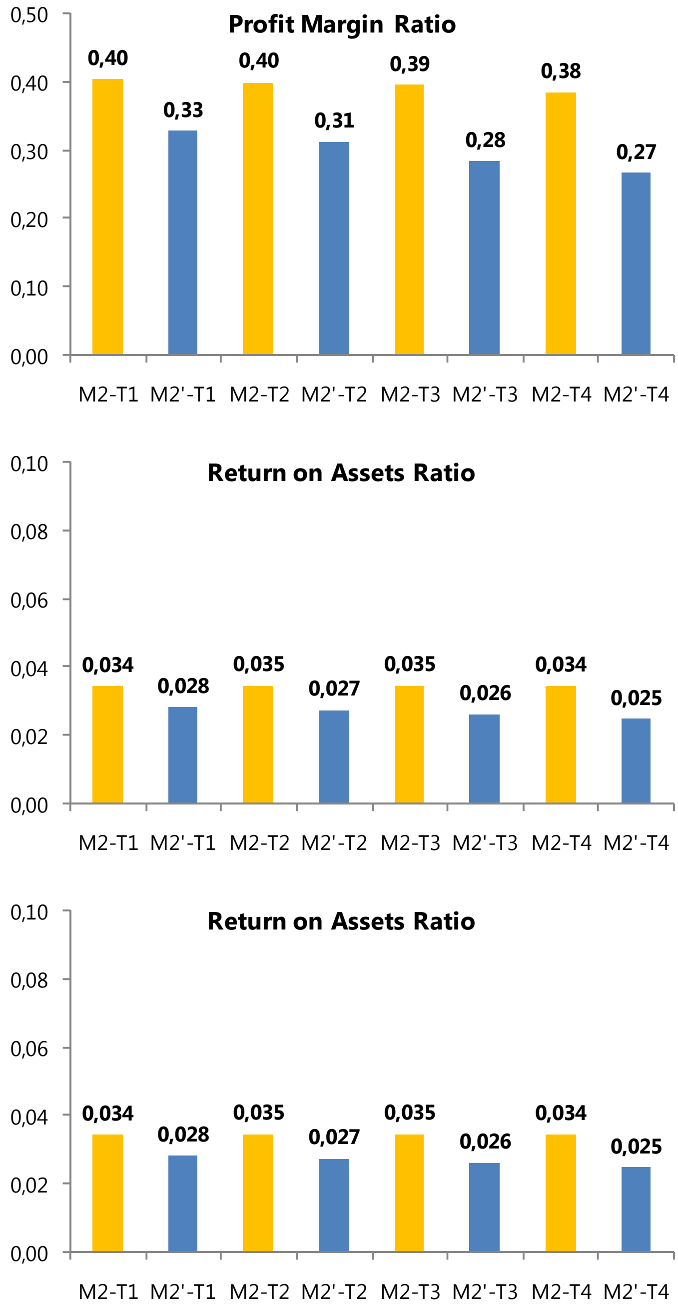


Figure 4-14: Profitability ratios of models M2 and M2′ at each time period

4.5 Computational experiments

Our mathematical formulation is generic and not specific to the above case study. The case study served to highlight the applicability of the model and the impact of financial statement analysis in the model. Hammami et al. (2008) mentioned that exact solution methods based essentially on the branch-and-bound algorithm are unlikely to be efficient for large size problems.

For this reason we conduct eight computational experiments for eight randomly generated instances, in order to evaluate our model's reaction to larger test-beds. Reaction is evaluated in terms of feasibility and computational times. Table 4-32 summarises the results of these tests. Instances 1 and 2 are increasing the number of time periods and demand scenarios. Instances 3 to 8 are increasing the number of products, plants, warehouses, distribution centres and customer zones.

Table 4-32: Computational results of models M2 and M2′

IN	PL	W	DC	CZ	P	T	S	CV	DV	LC	Time (sec)	
											M2	M2′
1	3	4	6	8	7	4	16	46,169	82	92,277	777.047	641.522
2	3	4	6	8	7	4	24	68,569	82	140,149	386.986	1594.602
3	4	4	6	8	7	4	8	25,359	82	47,381	1572.491	529.671
4	4	5	6	8	7	4	8	28,107	89	52,020	979.578	715.328
5	4	5	7	8	7	4	8	31,509	103	57,765	427.955	1435.113
6	4	5	7	9	7	4	8	33,259	110	60,796	432.061	1431.157
7	4	5	7	9	8	4	8	37,675	110	68,486	1234.955	1452.468
8	5	5	7	9	8	4	8	39,853	110	72,384	320.814	1921.492

Note: IN=Instance, PL=Plants, W=Warehouses, DC=Distribution centres, CZ=Customer zones, P=Products, T=Time periods, S=Scenarios, CV=Continuous variables, DV=Discrete variables, LC=Linear constraints.

The above results indicate that the proposed integrated modelling framework represented by a direct MIP model cannot be used for the solution of large-scale problems involving more than 25 products and customer zones and more than 20 production plants and warehouses/distributions centres. In this case special solution techniques should be investigated.

4.6 Concluding remarks

This chapter presented a model that integrates financial statement analysis and product demand uncertainty in the optimal design of SCN. The novel features of this model are the simultaneous considerations of the aforementioned issues and its convenient use as a strategic decision tool.

Furthermore, the modelling of demand uncertainty through scenarios gives SCN managers the ability to weight their demand forecasts, by assigning occurring possibilities on each scenario. With the same manner, SCN managers could correct their wrong forecasts, which might be due to unreliable forecasting techniques or due to dramatic economic changes in the marketplace. The modelling of financial statements enables SCN managers to take holistic decisions without underestimating the basic objective of a profit company, which is the creation of value for shareholders.

This objective dictates a satisfactory financial status in order to guarantee new funds from shareholders and financial institutions that will allow the continuously and uninterrupted financing of company's operations. The applicability of the proposed framework is illustrated by using a simple SCN. It was illustrated how financial considerations affect the optimal structure and operation of the network and the superiority of the model (M2) against a no financially constrained model (M2').

As SCNs are becoming more complicated in their design and operation the need for a purely financial model necessitates. Pure financial models should track the dynamics of a SCN in terms of money value associated with its financial operation. After the financial operation is optimised the solution should be used to optimise the design and operation of the SC in a two-stage programming model. Cash flow management, securities portfolio management, advanced financial engineering management and assets-liabilities management are among the financial operations that these models should formulate.

The proposed model could be extended by introducing more detailed financial modelling aspects and incorporation of issues related to: credit solvency, sell and leaseback techniques, product portfolio theory, game theory, future contracts, and hedging against risks.

CHAPTER 5

Managing the trade-offs between financial performance and credit solvency in the optimal design of SCNs under economic uncertainty

5.1 Introduction

A healthy financial status of a SCN is a mandatory condition that enables the uninterrupted flow of funds from external sources, such as banks and financial institutions, and internal sources, such as shareholders and creditors. In this way, the SCN continues its production and logistic operations and moreover seizes upon growth opportunities.

In Chapter 4 the financial status of a SCN was assessed and modelled through financial performance and financial ratios. Financial theory and economic logic have not yet provided a reliable guide on which financial ratios are more important, and which are less, in making judgments about a company's outlook. Some companies might have high liquidity and high solvency ratios in contrast to others where their solvency and liquidity ratios might be very low. A common practice in financial analysis is to use the industry leader as a benchmark. However, Helfert (2003), among others, argued that comparative analysis of companies and business is challenged by the frequent lack of truly comparable data, because of differences in product/service mix, accounting choices, size and age of the businesses, differences in the portfolio, and geographic scope.

Credit solvency is the measure that overcomes the limitation of which financial ratios are more appropriate to summarise and express a company's economic standing. Credit solvency along with financial performance provides investors a compact, convenient, and easily interpretable picture about a company's prospectus.

These two pillars have a discernible contribution on the SCN's ability to attract and earn the necessary funds in order to ensure perpetuity of production and distribution operations.

Although considered together, financial performance and credit solvency are not necessary moving to the same direction as each one has a different fundamental objective. The former focuses on increasing the wealth (profits, net present value of stocks, shareholder value, etc.) while the latter on minimising the default possibilities. As each of these pillars focuses on a different aspect of investment attractiveness, underlined trade-offs exist, under various economic conditions, and challenge further investigation.

This chapter develops a robust multi-objective mixed integer non linear programming (moMINLP) SCN design model capable of capturing the tradeoffs between financial performance and financial distress possibilities inherent in SCNs. In particular, the proposed model aimed at finding the optimal SCN configuration, under economic uncertainty, driven by two financial objectives, namely, EVA™ and Altman's Z-score and restricted by various structural and operational constraints.

The proposed model is differentiated from that presented in Chapter 4 in various ways. First, the model is a multi-objective MINLP problem, instead of single-objective MILP, due to the fact that both its objective functions are non linear. Second, the model accounts for economic uncertainty, instead of only product demand uncertainty. Third the SCN's financial status is not formulated as a set of target constraints set by the decision maker but is optimised via a multi-variate and unbiased indicator (Altman's Z-score). Finally, the WACC, which is a vital constituent of the EVA™, is an endogenous variable being optimised, instead of an exogenous estimated parameter.

Section 5.2 presents an importance justification for credit solvency, economic uncertainty, and WACC followed by a mathematical programming formulation in Section 5.3. The applicability of the developed model is illustrated in Section 5.4 by using a small-scale real case study. Finally, concluding remarks are drawn in Section 5.5.

5.2 Financial considerations

5.2.1 Credit solvency

The detection of a company's credit standing is a subject that has been particularly amenable to analysis with financial ratios. Although financial ratios have a definite potential as predictors of financial distress, many studies citing a different ratio as being the most effective indication of impeding problems. Hence, an appropriate extension and combination of several measures into a meaningful multivariate predictive model, with clear and not misleading results, is necessary (Altman & Hotchkiss, 2006).

The Altman's corporate credit scoring model (Altman, 1968) satisfied that need and with appropriate modifications has maintained its accuracy and relevance for over four decades since its original development. Its calculation formula is defined as:

$$\textbf{Z-score} = 1.2\frac{WC}{TA} + 1.4\frac{RE}{TA} + 3.3\frac{EBIT}{TA} + 0.6\frac{MVEQ}{BVTL} + 1.0\frac{NTS}{TA}$$

where (WC) is the working capital, (TA) are the total assets, (RE) are the retained earnings, (EBIT) are the earnings before interests and taxes, (MVEQ) is the market value of equity, (BVTL) is the book value of total liabilities, and (NTS) are the net sales.

When the resulting score is below **1.81** then the company has a high probability of default, while when it has a score of more than **2.99** it is solvent and financial healthy. A score between **1.81** and **2.99** indicates uncertain credit risks and attention alerts.

Financial distress became a major concern worldwide as the recent bankruptcies of industrial giants like General Motors, Enron, WorldCom, and Chrysler reveal weaknesses of the detection mechanisms. In the field of SCN modelling, none of the existing SCND or SCNO models, found scattered in the literature, incorporated any financial distress modelling aspect, to the best of the authors' knowledge.

5.2.2 Economic uncertainty

As eloquently presented in Section 2.3, uncertainty in SCN's is a mature issue that SCN researchers and managers have devoted their interest to for over two decades. Initially, demand uncertainty was the most investigated source of uncertainty, within SCN's, and this is reasonable as the early SCN's relied heavily on customer demand satisfaction. Competitive pressures along with the increasing complexity in the business environment have gradually add in the researchers' agenda other sources of uncertainty such as supply, capacities, inventories, and prices, just to name a few.

However, SCNs are also facing uncertainties and risks from the economic environment. While the benefits of uncertainty consideration in SCN design have been well documented in the literature, existing models are addressing downstream and upstream uncertainty without any focus on economic uncertainty. This source of uncertainty delineates both profits and core decisions within a SCN (Liu & Cruz, 2012) and therefore deserves meticulous investigation. Economic uncertainty refers to macroeconomic, financial, and market conditions that either partially or totally play a catalytic role in a SCN's financial performance and credit solvency.

We model economic uncertainty by employing the notion of economic cycle. Economic cycle is divided into three stages, namely, boom, stagnation, and recession, each of which has several macroeconomic, financial, and market conditions whose deviation express to a large extend the economic uncertainty. In our model seven parameters, reflecting the uncertain economic environment, are uncertain, namely, "product demand", "short-term interest rate", "long-term interest rate", "risk-free rate of interest", "expected return of the market", "underwriting cost", and "market liquidity".

During a boom period households and firms have an increased purchasing power and their consumption is increasing resulting in excessive demand for products and services. Short-term and long-term interest rates are decreasing as they incorporate less risk of borrowers' default. Risk-free rate of interest, which is usually the interest rate of a Treasury bill, is decreasing as the intensive economic activity yields more taxes for the state and thus the risk of default is decreasing. Expected return of the market, which is usually the return of the most representative stock market index, is increasing as investors oversee that this pick in economic activity will provide them more dividends and capital gains. Underwriting cost, which is the cost of issuing new equity in capital markets and raising capital for investment purposes, is decreasing as the underwriters' risk of holding the unsold underlying securities is low and the competition in the underwriting industry is immense in a capital market with fierce investing interest. Market liquidity, which is the cash, instead of checks, notes and credits, used to pay expenses, is increasing as financial institutions are less hesitant to provide money to both households and firms. On the other hand, during a recession period all the aforementioned parameters are moving to the contrary direction. In a stagnation period the deviations in these parameters is minor and the governing rule is that the past shapes the future.

5.2.3 Weighted average cost of capital (WACC)

The cost of capital has moved to the forefront of financial community since the seminal papers of Modigliani and Miller (1958, 1963) where the famous M&M propositions we introduced. Cost of capital is the expected rate of return that the market participants require in order to attract funds to a particular investment. The cost of capital estimate is the essential link that enables us to convert a stream of expected income into an estimate of present value and thus allow us to make informed pricing decisions for purchases and sales and to compare one investment opportunity against another (Pratt & Grabowski, 2008). There can be little doubt that the cost of capital is an extremely important business and financial tool. It is used in corporate business models to help determine company valuation and shape corporate strategy (Ogier et al., 2004). Two main components constitute the WACC whose calculation formula is defined as:

$$\mathbf{WACC} = K_e\frac{E}{V} + K_d(1\text{-}T)\frac{D}{V}$$

where (K_e) is the cost of equity, (K_d) is the cost debt, (E) is the value of equity, (D) is the value of debt, (V) is the sum of equity and debt values, and (T) is the corporate tax rate.

As the firm uses debt and equity capital to finance its operations, this overall cost of capital is a mixture of the returns needed to compensate its creditors and those needed to compensate its stockholders. Regarding cost of equity, unfortunately, there is not a way of directly observing the return that the firm's equity investors required on their investments and for this reason the Capital Asset Pricing Model (CAPM) is used as a surrogate (see the influential works of Markowitz (1952), Sharpe (1964), and Lintner (1965)). CAPM is an equation consisted of three terms and showing the expected return of a particular asset. Its calculation formula is defined as:

$$\mathbf{K_e} = r_f+(r_m-r_f) \times \beta$$

The first term is the risk-free rate of interest (r_f), the reward for placing capitals in an investment without taking any risk. The second term, the difference between expected return of the market (r_m) and r_f, is the reward for placing capitals in the market, and thus bearing an average amount of systematic risk, instead of placing capitals in an investment without taking any risk. The third term, the beta coefficient (β), is the amount of systematic risk present in a particular asset and relative to that in an average asset.

On the contrary, cost of debt can be observed directly because it is the interest rate the firm pays on new borrowing, which is defined in financial markets. As a firm has both short-term and long-term debt an appropriate weighting, based on the portion of each type of debt (STL, LTL) within its total debt (TL), is necessary. The weighted cost of debt is then multiplied with the term (1-TR) in order to account for the "tax shield" advantage of debt as debt financing, rather than equity financing, reduces tax bill. Finally, by multiplying each cost of capital with its corresponding capital structure weight, the portion of each source (E, STL & LTL) to total invested capital (IC), the WACC is calculated (Ogier et al., 2004; Ross et al., 2006).

In model M2, presented in Chapter 4, we consider that the WACC is a parameter estimated in advanced by company's decision makers and not a variable being optimised. Although financial managers might have accurate estimations on this figure or their errors might follow the normal distribution, it is more effective and valuable to relax this assumption and consider this vital constituent of the EVA™ as a part of the optimisation objective.

5.3 Mathematical formulation

5.3.1 Problem description

As in the two previous chapters, in this chapter the proposed model, which integrates credit solvency modelling, economic uncertainty handling, and WACC modelling, considers the design of a multiproduct, four-echelon SCN as shown in Figure 5-1. The problem under investigation is identical to that presented in Section 3.3.1 and in Section 4.3.1, where our main aim is to satisfy customers' product demand by establishing the optimal SCN in terms of financial performance and credit solvency. The latter along with economic uncertainty and WACC are the three features that distinguish that model from model M2 presented in Chapter 4. However, due to the fact that financial performance and credit solvency do not always follow parallel roads, tradeoffs exist and the optimal SCN configuration is not unique. Consequently, our aim becomes to provide not a unique solution but a set of alternative optimal SCN configurations.

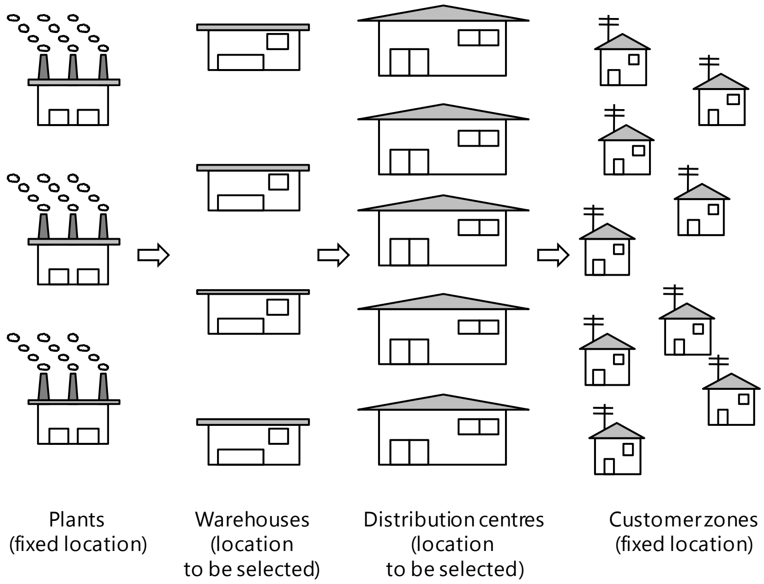


Figure 5-1: The SCN considered in this chapter

The SCN decisions to be determined by the proposed model are the same as those in models M1 and M2 along with four additional decisions regarding the structure of both assets and capital. We repeat the same decisions here for case of reference together with the newly introduced decisions.

Strategic decisions ("here-and-now"):

I. The number, location and capacity of warehouses to be set up
II. The number, location and capacity of distribution centres to be set up
III. The transportation links that need to be established in the network

and tactical ("wait-and-see"):

IV. The flows of products in the network
V. The production rates at plants
VI. The inventory levels at each warehouse
VII. The inventory levels at each distribution centre
VIII. The level of leverage

IX. The level of equity
X. The level of fixed assets
XI. The level of current assets

The objective is to find the set of optimal SCN configurations that maximise the company's average expected value of EVA™ and average expected value of Altman's Z-score, under all economic scenarios, over the planning horizon, taking into account several design, operating, and financial constraints.

5.3.2 Mathematical model (M3)

The above problem is formulated through a moMINLP problem (M3). In contrast to models M1 and M2, where uncertainty concerned only product demands, in model M3 uncertainty concerns the economic environment and is expressed though seven parameters presented in detail in Section 5.2.2. In model M3 these seven parameters are time-varying and uncertain and thus the dynamic nature is maintained. The scenario approach, as explained in detail in Section 3.2, is employed in handling transient economic uncertainty, and is shown in Figure 5-2 in order to keep coherency with the case study application that follows on Section 5.4.

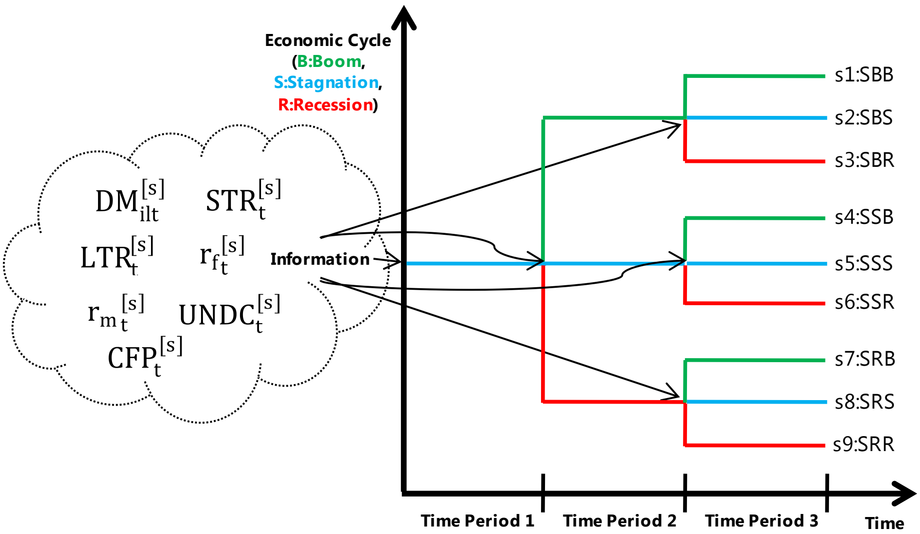


Figure 5-2: Scenarios for problems involving both "here-and-now" and "wait-and-see" decisions

The proposed model M3 handles any one of these scenarios, as M1 and M2 do, by multiplying each scenario with its probability to occur ψ_s. These probabilities satisfy the condition expressed by constraint (3.1):

$$\sum_{s=1}^{NS} \psi_s = 1 \tag{3.1}$$

5.3.3 Nomenclature

The nomenclature to be used in this chapter is consistent with that used in Chapter 3 for model M1 and in Chapter 4 for model M2. Here we present only those symbols that are different from those listed in Section 3.3.3 and in Section 4.3.3 and these are either newly introduced or substituting existing ones. A minor change is made in the variables expressing the production rate in plants and the transportation flows between successive nodes in the SCN. They are expressed as quantity of products instead of flows of material.

Indices

s economic scenario (substitutes *s* which represented product demand scenario)

Parameters

C_k^{DF}	fixed cost of establishing distribution centre at location *k* (substitutes C_k^{D})
C_m^{WF}	fixed cost of establishing warehouse at location *m* (substitutes C_m^{W})
$\mathrm{CFP}_t^{[s]}$	percent of net operating profits after taxes that are connected with cash flow at the end of period *t* under scenario *s* (substitutes CFP_t)
$\mathrm{DIVPAY}_t^{[s]}$	dividend payout ratio at the end of period *t* under scenario *s*
DREXFA_t	depreciation rate of existed fixed assets at the end of time period *t* (substitutes DR_t)
DRNWFA_t	depreciation rate of new fixed assets at the end of time period *t* (substitutes DR_t)
$\mathrm{LTR}_t^{[s]}$	long-term interest rate at the end time period *t* under scenario *s* (substitutes LTR_t)
MVS	market value of outstanding stocks
NS	number of economic scenarios (substitutes NS which represented number of product demand scenarios)
NT	number of time periods
NVS	nominal value of outstanding stocks
ORVEXFA	original value/ historical cost of existing fixed assets
Q_{jm}^{min}	minimum quantity of products that can practically and economically be transferred from plant *j* to warehouse *m* (substitutes rate of flow of material with quantity of products)

Q_{mk}^{min}	minimum quantity of products that can practically and economically be transferred from warehouse *m* to distribution centre *k* (substitutes rate of flow of material with quantity of products)
Q_{kl}^{min}	minimum quantity of products that can practically and economically be transferred from distribution centre *k* to customer zone *l* (substitutes rate of flow of material with quantity of products)
$\mathrm{Q}_{ijm}^{[s],max}$	maximum quantity of product *i* that can be transferred from plant *j* to warehouse *m* under scenario *s* (substitutes rate of flow with quantity of product)
$\mathrm{Q}_{imk}^{[s],max}$	maximum quantity of product *i* that can be transferred from warehouse *m* to distribution centre *k* under scenario *s* (substitutes rate of flow with quantity of product)
$\mathrm{Q}_{ikl}^{[s],max}$	maximum quantity of product *i* that can be transferred from distribution centre *k* to customer zone *l* under scenario *s* (substitutes rate of flow with quantity of product)
${\mathrm{r}_f}_t^{[s]}$	risk-free rate of interest during time period *t* under scenario *s*
${\mathrm{r}_m}_t^{[s]}$	expected return of the market during time period *t* under scenario *s*
SGAEX_t	selling general and administrative expenses during time period *t*
$\mathrm{STR}_t^{[s]}$	short-term interest rate at the end of time period *t* under scenario *s* (substitutes STR_t)
$\mathrm{UNDC}_t^{[s]}$	underwriting spread during time period *t* under scenario *s*

Continuous variables

$\mathrm{ADDRE}_t^{[s]}$	addition to retained earnings at the end of time period *t* under scenario *s*
$\mathrm{C}_t^{[s]}$	cash at the end of time period *t* under scenario *s* (substitutes C_t)
$\mathrm{CA}_t^{[s]}$	current assets at the end of time period *t* under scenario *s* (substitutes CA_t)
$\mathrm{CCP}_t^{[s]}$	contributed capital at the end of time period *t* under scenario *s*
$\mathrm{DIV}_t^{[s]}$	dividends paid at the end of time period *t* under scenario *s*
$\mathrm{EBIT}_t^{[s]}$	earnings before interests and taxes during time period *t* under scenario *s* (substitutes EBIT_t)
$\mathrm{E}_t^{[s]}$	equity at the end of time period *t* under scenario *s* (substitutes E_t)
$\mathrm{EXFA}_t^{[s]}$	existing fixed assets at the end time period *t* under scenario *s*

$\mathrm{FA}_t^{[s]}$	fixed assets at the end of time period *t* under scenario *s* (substitutes FA_t)
$\mathrm{IC}_t^{[s]}$	invested capital at the end of time period *t* under scenario *s* (substitutes IC_t)
$\mathrm{INR}_t^{[s]}$	value of inventory at the end of time period *t* under scenario *s* (substitutes INR_t)
$\mathrm{LTL}_t^{[s]}$	long-term liabilities at the end of time period *t* under scenario *s* (substitutes LTL_t)
$\mathrm{MVE}_t^{[s]}$	market value of equity at the end of time period *t* under scenario *s*
$\mathrm{NC}_t^{[s]}$	new cash at the end of time period *t* under scenario *s* (substitutes NC_t)
$\mathrm{NLTL}_t^{[s]}$	new long-term liabilities at the end of time period *t* under scenario *s* (substitutes NLTL_t)
$\mathrm{NSTL}_t^{[s]}$	new short-term liabilities at the end of time period *t* under scenario *s* (substitutes NSTL_t)
$\mathrm{NIS}_t^{[s]}$	new issued stocks at the end of time period *t* under scenario *s* (substitutes NIS_t)
$\mathrm{NISFC}_t^{[s]}$	new issued stocks earned for fixed capital investment purposes during time period *t* under scenario *s*
$\mathrm{NISWC}_t^{[s]}$	new issued stocks earned for working capital investment purposes during time period *t* under scenario *s*
$\mathrm{NTS}_t^{[s]}$	net sales during time period *t* under scenario *s* (substitutes NTS_t)
$\mathrm{NOPAT}_t^{[s]}$	net operating profits after taxes during time period *t* under scenario *s* (substitutes NOPAT_t)
$\mathrm{NOS}_t^{[s]}$	number of outstanding stocks at the end time period *t* under scenario *s*
$\mathrm{NWFA}_t^{[s]}$	newly fixed assets at the end time period *t* under scenario *s*
$\mathrm{P}_{ijt}^{[s]}$	production quantity of product *i* in plant *j* during time period *t* under scenario *s* (substitutes production rate with production quantity)
$\mathrm{Q}_{ijmt}^{[s]}$	quantity of product *i* transferred from plant *j* to warehouse *m* during time period *t* under scenario *s* (substitutes rate of flow with quantity of product)
$\mathrm{Q}_{imkt}^{[s]}$	quantity of product *i* transferred from warehouse *m* to distribution centre *k* during time period *t* under scenario *s* (substitutes rate of flow with quantity of product)

$\mathrm{Q}_{iklt}^{[s]}$	quantity of product i transferred from distribution centre k to customer zone l during time period t under scenario s (substitutes rate of flow with quantity of product)
$\mathrm{RA}_t^{[s]}$	receivable accounts at the end of time period t under scenario s (substitutes RA_t)
$\mathrm{RE}_t^{[s]}$	retained earnings at the end of time period t under scenario s
$\mathrm{STL}_t^{[s]}$	short-term liabilities at the end of time period t under scenario s (substitutes STL_t)
$\mathrm{WC}_t^{[s]}$	working capital at the end of time period t under scenario s
$\mathrm{WACC}_t^{[s]}$	weighted average cost of capital at the end of time period t under scenario s (substitutes the parameter WACC_t)

Greek letters

β	beta coefficient of the company
δ_{ij}	safety stock coefficient for product i held in plant j
δ_{ik}	safety stock coefficient for product i held in distribution centre k
δ_{im}	safety stock coefficient for product i held in warehouse m

5.3.4 Constraints

The basic structural and operational constraints are identical to those presented in Section 3.3.4 for model M1 and in Section 4.3.4 for model M2. However major changes took place in the financial modelling constraints as all financial variables are not independent of the scenario anymore. All existing and newly introduced financial variables have now a superscript [s] and the corresponding constraints are defined under each scenario. Additionally, the financial operation modelling has become more sophisticated and realistic as we clarify various aspects and introduce additional variables in order to formulate the credit solvency constituents.

Here we will present only those constraints that are different from those presented in Section 3.3.4 and in Section 4.3.4. These are either newly introduced or substituting existing ones. We explain thoroughly, in cases of constraints' updating, the underlying motivation.

Material balances constraints

In constraints (5.1)–(5.3) the term showing the accumulated product minus the exported product is not multiplied with the duration $\Delta\mathrm{T}_t$ as production and transportation are not expressed as flows anymore.

$$\mathrm{I}_{ijt}^{[s]} = \mathrm{I}_{ij,t-1}^{[s]} + \left(\mathrm{P}_{ijt}^{[s]} - \sum_m \mathrm{Q}_{ijmt}^{[s]}\right), \forall i,j,t,s = 1,\cdots,\mathrm{NS} \tag{5.1}$$

$$\mathrm{I}_{imt}^{[s]} = \mathrm{I}_{im,t-1}^{[s]} + \left(\sum_j \mathrm{Q}_{ijmt}^{[s]} - \sum_k \mathrm{Q}_{imkt}^{[s]}\right), \forall i,m,t,s = 1,\cdots,\mathrm{NS} \tag{5.2}$$

$$\mathrm{I}_{ikt}^{[s]} = \mathrm{I}_{ik,t-1}^{[s]} + \left(\sum_m \mathrm{Q}_{imkt}^{[s]} - \sum_l \mathrm{Q}_{iklt}^{[s]}\right), \forall i,k,t,s = 1,\cdots,\mathrm{NS} \tag{5.3}$$

Safety stock constraints

In constraints (5.4)–(5.6) the a priori set minimum inventory requirements, in constraints (3.22)–(3.24), could better satisfy their core scope, which is to overcome unforeseen production disturbances or unexpected product demands, if expressed as a percent of the quantity of products delivered by the node to all nodes supplied by it. Note that in contrast to models M1 and M2, where these safety stock requirements were measured in number of days equivalent of material flow, in model M3 are expressed as a percent of quantity exported to next node.

$$\mathrm{I}_{ijt}^{[s],min} = \delta_{ij} \sum_m \mathrm{Q}_{ijmt}^{[s]}, \forall i,j,t,s = 1,\cdots,\mathrm{NS} \tag{5.4}$$

$$\mathrm{I}_{imt}^{[s],min} = \delta_{im} \sum_k \mathrm{Q}_{imkt}^{[s]}, \forall i,m,t,s = 1,\cdots,\mathrm{NS} \tag{5.5}$$

$$\mathrm{I}_{ikt}^{[s],min} = \delta_{ik} \sum_l \mathrm{Q}_{iklt}^{[s]}, \forall i,j,k,s = 1,\cdots,\mathrm{NS} \tag{5.6}$$

Non-negativity constraints

Constraints (5.7)–(5.65) are the result of either newly introduced variables in model M3 or modifications of existing ones.

$$\mathrm{ADDRE}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.7}$$

$$\mathrm{C}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.8}$$

$$\mathrm{CA}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.9}$$

$$\mathrm{CCP}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.10}$$

$$\mathrm{DIV}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.11}$$

$$\mathrm{EBIT}_t^{[s]} \geq 0, \forall t,s = 1,\cdots,\mathrm{NS} \tag{5.12}$$

$$\mathrm{E}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.13}$$

$$\mathrm{EXFA}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.14}$$

$$\mathrm{FA}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.15}$$

$$\mathrm{IC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.16}$$

$$\mathrm{INR}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.17}$$

$$\mathrm{LTL}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.18}$$

$$\mathrm{MVE}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.19}$$

$$\mathrm{NC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.20}$$

$$\mathrm{NLTL}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.21}$$

$$\mathrm{NSTL}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.22}$$

$$\mathrm{NIS}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.23}$$

$$\mathrm{NISFC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.24}$$

$$\mathrm{NISWC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.25}$$

$$\mathrm{NTS}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.26}$$

$$\mathrm{NOPAT}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.27}$$

$$\mathrm{NOS}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.28}$$

$$\mathrm{NWFA}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.29}$$

$$\mathrm{RA}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.30}$$

$$\mathrm{RE}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.31}$$

$$\mathrm{STL}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.32}$$

$$\mathrm{WC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.33}$$

$$\mathrm{WACC}_t^{[s]} \geq 0, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.34}$$

Financial operation constraints

The financial operation constraints are defined for each time period *t* and for each scenario *s*, in contrast to corresponding constraints presented in Section 4.3.4.8 where the aforementioned constraints were defined only for each time period *t*. Although the modelling approach is the same and is driven by the two most important financial statements, namely income statement and balance sheet, we present here all financial constraints in a more compact way.

The income statement is formulated via constraints (5.35) to (5.61). Initially in constraint (5.35) net sales are calculated as the sum of product's price and demand.

$$\mathrm{NTS}_t^{[s]} = \sum_{i,l} \mathrm{PRICE}_{ilt}^{[s]} \mathrm{DM}_{ilt}^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.35}$$

By subtracting various operating and non operating expenses from net sales the result is earnings before interest and taxes. These expenses concern: (a) production cost; (b) transportation cost from plants to warehouses, from warehouses to distribution centres, and from distribution centres to customer zones; (c) product handling cost in warehouses, and in distribution centres; (d) inventory cost in plants, in warehouses, and in distribution centres; (e) selling general and administrative expenses; and (f) depreciation.

$$\begin{aligned}
\mathrm{EBIT}_t^{[s]} &= \mathrm{NTS}_t^{[s]} \\
&-\left(\sum_{i,j} \mathrm{C}_{ij}^{P} \mathrm{P}_{ijt}^{[s]}\right) \\
&-\left(\sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]} + \sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]} + \sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]}\right) \\
&-\left(\sum_{i,m} \mathrm{C}_{im}^{WH}\left(\sum_j \mathrm{Q}_{ijmt}^{[s]}\right) + \sum_{i,k} \mathrm{C}_{ik}^{DH}\left(\sum_m \mathrm{Q}_{imkt}^{[s]}\right)\right) \\
&-\left(\sum_{i,j} \mathrm{C}_{ij}^{I} \frac{\mathrm{I}_{ijt}^{[s]}+\mathrm{I}_{ij,t-1}^{[s]}}{2} + \sum_{i,m} \mathrm{C}_{im}^{I} \frac{\mathrm{I}_{imt}^{[s]}+\mathrm{I}_{im,t-1}^{[s]}}{2} + \sum_{i,k} \mathrm{C}_{ik}^{I} \frac{\mathrm{I}_{ikt}^{[s]}+\mathrm{I}_{ik,t-1}^{[s]}}{2}\right) \\
&-\mathrm{SGAEX}_t \\
&-\mathrm{DREXFA}_t \mathrm{ORVEXFA} \\
&-\mathrm{DRNWFA}_t\left(\sum_m \mathrm{C}_m^{WF} \mathrm{PW}_m + \sum_k \mathrm{C}_k^{DF} \mathrm{PDC}_k\right), \forall t, s = 1, \cdots, \mathrm{NS}
\end{aligned} \tag{5.36}$$

Expenses (a) to (d), which are realised in order to transform raw materials to products and deliver them to final customers, constitute the COGS. With the exception of inventory cost, all aforementioned expenses are calculated as the sum of product's unit cost and quantity of product produced, transferred, or handled. Regarding inventory cost, the arithmetic mean of the starting and finishing inventories is multiplied with the unit inventory cost as inventories vary linearly over each time period. Selling general and administrative (SGAEX_t) are expenses needed to sell products (salaries of sales people, commissions and travel expenses, advertising, freight, shipping, depreciation of sales store buildings and equipment) and manage the business (salaries of officers/executives, legal and professional fees, utilities, insurance, depreciation of office building and equipment, office rents). Depreciation is divided into this related to existing fixed assets and this related to newly established fixed assets due SCN's configuration. The former is calculated as the product of depreciation rate (DREXFA_t) and historical cost of these existing fixed assets while the latter is calculated as the product of depreciation rate (DRNWFA_t) and establishing cost of all newly fixed assets (warehouses and distribution centres).

Constraint (5.37) calculates net operating profits after taxes by subtracting short-term interests and long-term interests from EBIT and then multiplying the result with the term unity minus the corporate income taxes rate. Short-term and long-term interests are the product of interest rates with their corresponding liabilities.

$$\mathrm{NOPAT}_t^{[s]} = \left(\mathrm{EBIT}_t^{[s]} - \mathrm{STR}_t^{[s]}\mathrm{STL}_t^{[s]} - \mathrm{LTR}_t^{[s]}\mathrm{LTL}_t^{[s]}\right)(1 - \mathrm{TR}_t), \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.37)$$

Finally, NOPAT is allocated between dividends ($\mathrm{DIV}_t^{[s]}$) and addition to retained earnings ($\mathrm{ADDRE}_t^{[s]}$). The former, as shown in constraint (5.38), is the product of NOPAT and dividend payout ratio (DIDPAY_t) while the latter, as shown in constraint (5.39), is the remaining part if dividends are subtracted from NOPAT.

$$\mathrm{DIV}_t^{[s]} = \mathrm{NOPAT}_t^{[s]}\mathrm{DIDPAY}_t, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.38)$$

$$\mathrm{ADDRE}_t^{[s]} = \mathrm{NOPAT}_t^{[s]} - \mathrm{DIV}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.39)$$

Constraints (5.40) to (5.57) formulate the balance sheet. Beginning with the basic equation of the balance sheet, where the left side equals the right, constraint (5.40) forces the sum of fixed assets, cash, accounts receivable, and inventory to be equal with the sum of shareholders' equity, short-term liabilities, and long-term liabilities.

$$\mathrm{FA}_t^{[s]} + \mathrm{C}_t^{[s]} + \mathrm{RA}_t^{[s]} + \mathrm{INR}_t^{[s]} = \mathrm{E}_t^{[s]} + \mathrm{STL}_t^{[s]} + \mathrm{LTL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.40)$$

Constraint (5.41) defines that total assets ($\mathrm{TA}_t^{[s]}$) are the accounts presented in the left side of the balance sheet. Fixed assets are divided into existing ($\mathrm{EXFA}_t^{[s]}$) and newly ($\mathrm{NWFA}_t^{[s]}$) as shown in constraint (5.42). Existing fixed assets are those assets owned by the company before the SCN's configuration, such as property, plant, equipment, etc. while newly fixed assets are those assets (warehouses and distribution centres) established due to SCN's configuration.

$$\mathrm{TA}_t^{[s]} = \mathrm{FA}_t^{[s]} + \mathrm{C}_t^{[s]} + \mathrm{RA}_t^{[s]} + \mathrm{INR}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.41)$$

$$\mathrm{FA}_t^{[s]} = \mathrm{EXFA}_t^{[s]} + \mathrm{NWFA}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.42)$$

According to GAAP the cost of establishing/acquiring fixed assets should not encumber totally the fiscal period in which this establishment/acquisition took place but all fiscal periods (asset's estimated useful live) that benefit from their use. Depreciation is the allocation of the cost of fixed assets to the fiscal periods that benefit from their use as a means of matching expenses with revenues because if this huge cost was attributed to only one fiscal period the profitability information, gained from the income statement, would have been misleading. Hence, at each fiscal period a percent of assets' historical cost (establishment/acquisition cost) is subtracted from revenues in the form of depreciation and the net value of fixed assets presented in the balance sheet is the assets' historical cost minus accumulated depreciation.

Constraint (5.43) defines that existing fixed assets are calculated as the previous period's existing fixed assets minus depreciation. In expressing the newly fixed assets a distinction between the first period and the following periods is necessary. As the decision to establish a warehouse and a distribution centre is taken at the beginning of the planning period, previous period's newly fixed assets do not exist. Thus, as shown in constraint (5.44a), the newly fixed assets at the end of the first period are calculated as the establishment cost of these warehouses and distribution centres minus depreciation for the current period while for the following periods are calculated as the previous period's newly fixed assets minus depreciation, as shown in constraint (5.44b).

$$\mathrm{EXFA}_t^{[s]} = \mathrm{EXFA}_{t-1}^{[s]} - \mathrm{DREXFA}_t \mathrm{ORVEXFA}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.43)$$

$$\mathrm{NWFA}_t^{[s]} = (1 - \mathrm{DRNWFA}_t)$$
$$\left(\sum_m \mathrm{C}_m^{WF}\, \mathrm{PW}_m + \sum_k \mathrm{C}_k^{DF} \mathrm{PDC}_k\right), \forall t = 1, s = 1, \cdots, \mathrm{NS} \quad (5.44a)$$

$$\mathrm{NWFA}_t^{[s]} = \mathrm{NWFA}_{t-1}^{[s]}$$
$$-\mathrm{DRNWFA}_t\left(\sum_m \mathrm{C}_m^{WF}\, \mathrm{PW}_m + \sum_k \mathrm{C}_k^{DF} \mathrm{PDC}_k\right), \forall t > 1, s = 1, \cdots, \mathrm{NS} \quad (5.44b)$$

Constraint (5.45) defines current assets, which are the most liquid assets, as the sum of cash, accounts receivable, and inventory. Cash is defined in constraint (5.46) as the previous period's cash plus a percent of addition to retained earnings ($\mathrm{CFP}_t^{[s]}\mathrm{ADDRE}_t^{[s]}$), a surrogate for market liquidity as previously discussed in Section 5.2.2, plus new cash from the financial cycle of the current fiscal period, and plus new cash from SEO through new issued stock for working capital investment purposes ($\mathrm{NISWC}_t^{[s]}$).

$$\mathrm{CA}_t^{[s]} = \mathrm{C}_t^{[s]} + \mathrm{RA}_t^{[s]} + \mathrm{INR}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.45)$$

$$\mathrm{C}_t^{[s]} = \mathrm{C}_{t-1}^{[s]} + \mathrm{CFP}_t^{[s]}\mathrm{ADDRE}_t^{[s]}$$
$$+\mathrm{NC}_t^{[s]} + \left(1 - \mathrm{UNDC}_t^{[s]}\right)\mathrm{NISWC}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \quad (5.46)$$

When a company needs great amounts of funds in order to finance its fixed assets or/and its working capital it can refer to capital markets instead of financing from banks and financial institutions. However, this process has various expenses (underwriting fees, fees related to legal and accounting advisors, and printing costs) that are generally expressed as a percent of raised capital. In practice this percent is the difference between the underwriter's buying price and the offering price and is called "gross spread" or "underwriting discount" ($\mathrm{UNDC}_t^{[s]}$). Hence, the term

$(1-\mathrm{UNDC}_t^{[s]})$ is multiplied with the sum of new issued stocks for working capital investment purposes in order to present the net value of cash directed to the company's cash reserves.

Accounts receivable, the other constituent of current assets, is defined in constraint (5.47) as the previous period's accounts receivable plus the remaining percent of addition to retained earnings. Inventories, the last constituent of current assets, is calculated as the sum of the product between minimum production cost for each product ($\min_i\{\mathrm{C}_{ij}^P\}$) and sum of all inventories of each product, as shown in constraint (5.48). Inventories are valued with the minimum production cost due to historical cost accounting and GAAP's principle of prudence.

$$\mathrm{RA}_t^{[s]} = \mathrm{RA}_{t-1}^{[s]} + \left(1-\mathrm{CFP}_t^{[s]}\right)\mathrm{ADDRE}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.47}$$

$$\mathrm{INR}_t^{[s]} = \textstyle\sum_{i,j,m,k} \min_i\{\mathrm{C}_{ij}^P\}\left(\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{imt}^{[s]} + \mathrm{I}_{ikt}^{[s]}\right), \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.48}$$

Constraint (5.49) defines total invested capital as the sum of shareholders equity, short-term liabilities, and long-term liabilities. Equity, as shown in constraint (5.50), is defined as the sum of contributed capital ($\mathrm{CCP}_t^{[s]}$) and retained earnings ($\mathrm{RE}_t^{[s]}$). In constraint (5.51) contributed capital is defined as the previous period's contributed capital plus new issued stock gained from capital markets via IPO or SEO.

However, a distinction in the calculation of new issued stock between the first period and all the following periods should be made. The first time period, due to fixed assets' establishment, all capitals gained should be directed to fixed capital investment purposes while for the following periods all capitals gained, if needed, should be directed to working capital investment purposes. On these lines, constraint (5.52a) states that first period's new issued stock is equal to new issued stock for fixed capital investment purposes ($\mathrm{NISFC}_t^{[s]}$) and constraint (5.52b) states that, for all successive periods, new issued stock is equal to new issued stock for working capital investment purposes ($\mathrm{NISWC}_t^{[s]}$). Another important issue, regarding new issued stock for working capital investment purposes, is that it cannot exceed the previous period's contributed capital due to legal restrictions, as shown in constraint (5.53).

$$\mathrm{IC}_t^{[s]} = \mathrm{E}_t^{[s]} + \mathrm{STL}_t^{[s]} + \mathrm{LTL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.49}$$

$$\mathrm{E}_t^{[s]} = \mathrm{CCP}_t^{[s]} + \mathrm{RE}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.50}$$

$$\mathrm{CCP}_t^{[s]} = \mathrm{CCP}_{t-1}^{[s]} + \mathrm{NIS}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.51}$$

$$\mathrm{NIS}_t^{[s]} = \mathrm{NISFC}_t^{[s]}, \forall t = 1, s = 1, \cdots, \mathrm{NS} \tag{5.52a}$$

$$\mathrm{NIS}_t^{[s]} = \mathrm{NISWC}_t^{[s]}, \forall t > 1, s = 1, \cdots, \mathrm{NS} \tag{5.52b}$$

$$\mathrm{NISWC}_t^{[s]} \leq \mathrm{CCP}_{t-1}^{[s]}, \forall t > 1, s = 1, \cdots, \mathrm{NS} \tag{5.53}$$

Constraint (5.54), defines retained earnings as the previous period's retained earnings plus addition to retained earnings. Total liabilities ($\mathrm{TL}_t^{[s]}$) are the sum of short-term liabilities and long-term liabilities, as shown in constraint (5.55). Short-term liabilities are defined in constraint (5.56) as the previous period's short-term liabilities plus new short-term liabilities from the financial cycle of the current fiscal period. In the same manner, long-term liabilities are defined in constraint (5.57) as the previous period's long-term liabilities plus new long-term liabilities from the financial cycle of the current fiscal period.

$$\mathrm{RE}_t^{[s]} = \mathrm{RE}_{t-1}^{[s]} + \mathrm{ADDRE}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.54}$$

$$\mathrm{TL}_t^{[s]} = \mathrm{STL}_t^{[s]} + \mathrm{LTL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.55}$$

$$\mathrm{STL}_t^{[s]} = \mathrm{STL}_{t-1}^{[s]} + \mathrm{NSTL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.56}$$

$$\mathrm{LTL}_t^{[s]} = \mathrm{LTL}_{t-1}^{[s]} + \mathrm{NLTL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.57}$$

Working capital is defined in constraint (5.58) as current assets minus short-term liabilities. The number of outstanding stocks ($\mathrm{NOS}_t^{[s]}$) is defined in constraint (5.59) by dividing contributed capital with nominal value of stocks (NVS). Market value of equity ($\mathrm{MVE}_t^{[s]}$) is the product of number of outstanding stocks and market value of stocks (MVS), as shown in constraint (5.60). Finally, the total establishment cost of warehouses and distribution centres, due to SCN's configuration realised in the first period, should be financed by a combination of new issued stock for fixed capital investment purposes and new long-term liabilities, as shown in constraint (5.61). Again, the term $(1 - \mathrm{UNDC}_t^{[s]})$ is multiplied with the sum of new issued stocks for fixed capital investment purposes in order to present the net value of cash earned in order to pay the fixed assets' establishment cost.

$$\mathrm{WC}_t^{[s]} = \mathrm{CA}_t^{[s]} - \mathrm{STL}_t^{[s]}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.58}$$

$$\mathrm{NOS}_t^{[s]} = \frac{\mathrm{CCP}_t^{[s]}}{\mathrm{NVS}}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.59}$$

$$\mathrm{MVE}_t^{[s]} = \mathrm{NOS}_t^{[s]}\mathrm{MVS}, \forall t, s = 1, \cdots, \mathrm{NS} \tag{5.60}$$

$$\textstyle\sum_m \mathrm{C}_m^{\mathrm{WF}}\, \mathrm{PW}_m + \sum_k \mathrm{C}_k^{DF} \mathrm{PDC}_k = \left(1 - \mathrm{UNDC}_t^{[s]}\right) \mathrm{NISFC}_t^{[s]}$$

$$+\mathrm{NLTL}_t^{[s]}, \forall t = 1, s = 1, \cdots, \mathrm{NS} \tag{5.61}$$

While we have finished with the revised financial modelling as well as with the modelling of additional financial aspects, needed in order to reach objective function constituents, we mention at this point the modifications and additions made into the financial operation constraints formulation presented in Section 4.3.4.

In model M3 presented in this chapter we made the following changes:

- We express the income statement in a more compact way consisted of five constraints instead of 11 presented in model M2.
- We divide depreciation between existed fixed assets and newly established as it is common to apply different depreciation rates in assets with different maturity or/and utilisation.
- We incorporate selling, general and administrative expenses within income statement modelling.
- We specialise NOPAT by separating it into dividends and addition to retained earning with the latter being transferred to the balance sheet. In model M2 all the NOPAT was directed to the balance sheet.
- We express the establishment of fixed assets as an instantly procedure. The establishment cost is fixed and takes place at the beginning of the planning horizon rather than in a periodic basis as in Model M2. Most investment projects require entire payment in advance instead of periodic payments so this modification is considered more realistic.
- We allow model M3 to receive cash not only from the transfer of a part of NOPAT, from the income statement to the balance sheet, but also from an IPO/SEO for working capital investment purposes and from the financial operation the company.
- We measure the value of inventories with the lowest production cost of each product among all plants and not with the production cost at the plant where the product was produced.
- We specialise the equity constraint by merging the previous period's equity and the new issued stock into contributed capital. The latter is increased when new stocks are issued for fixed capital investments or/and for working capital investments.
- We express working capital, number of outstanding stocks, and market value of equity.
- We forced model M3 to finance the SCN's establishment cost through a mixture of new issued stocks and new long-term liabilities.

5.3.5 Objective functions

The objective of the optimisation problem is to find the set of optimal SCN configurations that maximise the company's average expected value of EVA™ and average expected value of Altman's Z-score, under all economic scenarios and during the planning horizon. While our model M3 is multi-objective we have two objective functions.

The first objective function formulates the average expected value of EVA™ as previously introduced in Section 4.2.2 and expressed mathematically in Section 4.3.5. However, in contrast to model M2, in model M3 the WACC is optimised rather than estimated in advance and this is a novel enrichment of the model M2. The second objective function formulates the average expected value of Altman's Z-score as previously introduced in Section 5.2.1.

$$\mathrm{OBJ}^{3a}\text{: max } \frac{1}{\mathrm{NT}} \sum_t^{NT} \sum_s^{NS} \psi_s \left\{ \mathrm{NOPAT}_t^{[s]} - \left[\underbrace{\left(\frac{\mathrm{E}_t^{[s]}}{\mathrm{IC}_t^{[s]}} \underbrace{\left(\mathrm{r}_{f\,t}^{[s]} + \left(\mathrm{r}_{m\,t}^{[s]} - \mathrm{r}_{f\,t}^{[s]} \right) \beta \right)}_{\text{Cost of equity}} \right) + \left(\frac{\mathrm{STL}_t^{[s]} + \mathrm{LTL}_t^{[s]}}{\mathrm{IC}_t^{[s]}} \underbrace{\left(\frac{\mathrm{STL}_t^{[s]}}{\mathrm{TL}_t^{[s]}} \mathrm{STR}_t^{[s]} + \frac{\mathrm{LTL}_t^{[s]}}{\mathrm{TL}_t^{[s]}} \mathrm{LTR}_t^{[s]} \right)}_{\text{Cost of debt}} (1 - \mathrm{TR}_t) \right)}_{\text{WACC}} \right] \mathrm{IC}_t^{[s]} \right\}$$

$$\mathrm{OBJ}^{3b}\text{: max } \frac{1}{\mathrm{NT}} \sum_t^{NT} \sum_s^{NS} \psi_s \left[1.2 \left(\frac{\mathrm{WC}_t^{[s]}}{\mathrm{TA}_t^{[s]}} \right) + 1.4 \left(\frac{\mathrm{RE}_t^{[s]}}{\mathrm{TA}_t^{[s]}} \right) + 3.3 \left(\frac{\mathrm{EBIT}_t^{[s]}}{\mathrm{TA}_t^{[s]}} \right) + 0.6 \left(\frac{\mathrm{MVE}_t^{[s]}}{\mathrm{TL}_t^{[s]}} \right) + 1.0 \left(\frac{\mathrm{NTS}_t^{[s]}}{\mathrm{TA}_t^{[s]}} \right) \right]$$

5.3.6 Solution approach

The above mathematical model including objective functions OBJ^{3a} and OBJ^{3b} and constraints (3.1)–(3.11), (3.15)–(3.24), (3.28)–(3.36), (4.1), and (5.1)–(5.61) is a Non-Convex moMINLP that is solved by using the standard e-constraint method and branch-and-bound techniques. The nonlinearities arise in both objective functions.

Multi-objective optimisation is an area of research on management science and a decision tool for engineers, managers, and planners. In contrast to traditional optimisation, where the problem is straightforward and the point of optimality is objectively determined and in many cases is unique, in multi-objective optimisation the decision maker's preference is essential as optimality is a set of different points in a frontier called efficient, or non-dominated, or Pareto optimal, or Pareto admissible, and this is because the goals are conflicting and cannot be reduced to a common scale of cost or benefit (Rosenthal, 1985; Tabucanon, 1996).

Considering an arbitrary optimisation problem with q objectives that are all to be maximised. A solution to this problem can be described in terms of a $decision\ vector$ $(x_1, x_2, \dots, x_p)$ in the $decision\ space$ $\boldsymbol{X}$. A function $\boldsymbol{f}: \boldsymbol{X} \rightarrow \boldsymbol{Y}$ evaluates the quality of a specific solution by assigning it an $objective\ vector$ $(y_1, y_2, \dots, y_q)$ in the $objective\ space$ $\boldsymbol{Y}$. Supposing that the objective space is a subset of real numbers ($\boldsymbol{Y} \subseteq \mathbb{R}$) and that the goal of optimisation is to maximise the single objective, a solution $\boldsymbol{x}^1 \in \boldsymbol{X}$ is better than another solution $\boldsymbol{x}^2 \in \boldsymbol{X}$ if $\boldsymbol{y}^1 > \boldsymbol{y}^2$ where $\boldsymbol{y}^1 = \boldsymbol{f}(\boldsymbol{x}^1)$ and $\boldsymbol{y}^2 = \boldsymbol{f}(\boldsymbol{x}^2)$. Although several optimal solutions may exist in the decision space, they are all mapped to the same objective vector. In the case of a vector-valued evaluation function $\boldsymbol{f}$ with $\boldsymbol{Y} \subseteq \mathbb{R}^{\boldsymbol{q}}$ and $q > 1$, the situation of comparing two solutions $\boldsymbol{x}^1$and $\boldsymbol{x}^2$ is more complex. Following the well known concept of Pareto dominance, an objective vector $\boldsymbol{y}^1$ is said to $dominate$ another objective vector $\boldsymbol{y}^2$ ($\boldsymbol{y}^1 \succ \boldsymbol{y}^2$) if no component of $\boldsymbol{y}^1$ is smaller than the corresponding component of $\boldsymbol{y}^2$ and at least one component is greater. Accordingly, a solution $\boldsymbol{x}^1$ is better to another solution $\boldsymbol{x}^2$, $\boldsymbol{x}^1$ $dominates$ $\boldsymbol{x}^2$ ($\boldsymbol{x}^1 \succ \boldsymbol{x}^2$), if $\boldsymbol{f}(\boldsymbol{x}^1)$ dominates $\boldsymbol{f}(\boldsymbol{x}^2)$. In this case, optimal solutions may be mapped to different objective vectors meaning that there exist several optimal objective vectors representing different trade-offs between these objectives (Zitzler, Laumanns, & Bleuler, 2004).

In this chapter the e-constraint method, one of the most frequently used in practical problems (Miettinen, 1999) and in SCN design/planning (Liu & Papageorgiou, 2013), is utilised in order to construct the efficient frontier. This method was introduced by Haimes et al. (1971) and is based on the maximisation of one objective function while considering the other objectives as constraints bounded by some allowable levels e_j. A systematic variation of yields a set of Pareto optimal solutions provided that these solutions have active ε-constraints (Carmichael, 1980). Therefore the following MINLP formulation is applied in our problem in order to generate the Pareto solutions:

Maximise OBJ^{3a} ***subject to*** $\mathrm{OBJ}^{3b} \geq e_j$ ***and to constraints (3.1)–(3.11), (3.15)–(3.24), (3.28)–(3.36), (4.1), and (5.1)–(5.61).***

Appropriate values for e_j are selected via a general mathematical guideline provided by Carmichael (1980). By changing the bound level e_j, OBJ^{3a} takes different value and the collection of all these pairs of points form the set of Pareto efficient solutions that might be represented in a two dimensional chart where each point in the efficient frontier implies a SCN configuration.

5.4 A case study

5.4.1 Background

The applicability of the proposed moMINLP model M3 is illustrated through its implementation in the same industrial company presented in Chapter 3 and in Chapter 4. However, the size of the problem is not the same, as in Sections 3.4.1 and 4.4.1, and the data are not identical because they are measured in quantity of items instead of tonnes. In many cases the nodes of the SCN either fixed (plant and customer zones) or potential (warehouses and distribution centres) are not the same as in those in Sections 3.4.1 and 4.4.1. For this reason we will provide all data.

There are two production plants which consume four shared manufacturing resources and produce eight products. These products should arrive at eight customer zones located in different places, in order to satisfy their demands, through a network of three potential warehouses and four potential distribution centres, as shown in Figure 5-3.

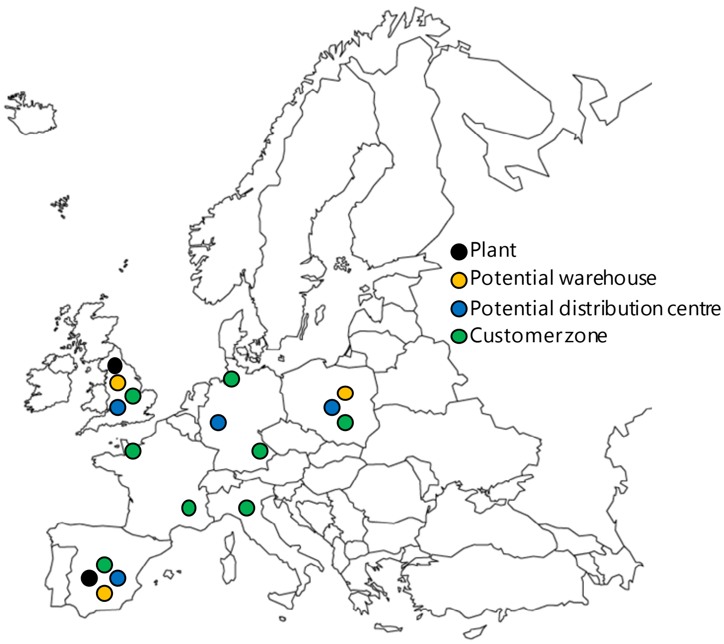


Figure 5-3: The case study SCN

For confidentiality reasons the locations of plants, warehouses, distribution centres, and customer zones are referred with numbers and for the financial data the relative money units have substitute the real currency units.

Plants

Each plant produces all products from a portfolio of eight different products using four share production resources and subjected to a maximum production capacity.

Table 5-1 presents the utilization of these share manufacturing resources along with the total resource availability, while the maximum production capacity of each plant is provided in Table 5-2.

Table 5-1: Utilization & availability of resource *e* for product *i* in plant *j**

Plant	Shared resource utilization coefficient ρ_{ije} (h/i)								R_{je} (h/y) x 10^3
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	
$j_1 \cdot e_1$	0.0381	0.0425	0.0265	0.0450	0.0850	0.0000	0.0000	0.0000	150
$j_1 \cdot e_2$	0.0070	0.0065	0.0325	0.0211	0.0550	0.0560	0.0560	0.0556	120
$j_1 \cdot e_3$	0.0000	0.0250	0.0000	0.0000	0.0560	0.0450	0.0475	0.0758	188
$j_1 \cdot e_4$	0.0000	0.0265	0.0758	0.0325	0.0000	0.0780	0.0455	0.0658	185
$j_2 \cdot e_1$	0.0000	0.0000	0.0125	0.0458	0.0458	0.0236	0.0250	0.0524	188
$j_2 \cdot e_2$	0.0152	0.0125	0.0654	0.0584	0.0000	0.0564	0.0000	0.0855	190
$j_2 \cdot e_3$	0.0758	0.0750	0.0878	0.0000	0.0854	0.0789	0.0152	0.0980	170
$j_2 \cdot e_4$	0.0125	0.0000	0.0450	0.0850	0.0584	0.0458	0.0878	0.0000	169

* There is no difference among several scenarios and time periods.
Note: h/i means hours per item and h/y means hours per year.

The minimum production capacity is assumed to be zero. The minimum quantity of products that can practically and economically be transferred to each warehouse is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Table 5-2: Maximum production capacity of plant *j* for product *i**

Plant	Product (i/y)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
j_1	2550	2500	2900	2000	2750	2800	2150	2950
j_2	2700	2950	2800	2700	2950	2800	2700	2950

* There is no difference among several scenarios and time periods.
Note: i/y means item per year.

Each plant generates costs because of production, storage, and transportation of products to warehouses. Table 5-3 presents the unit production and storage cost in each plant, whereas Table 5-4 provides the unit transportation cost from plants to potential warehouses. In each plant and for each product there are initial inventories, equal to 10 percent of the maximum production capacity of the plant. For every plant a safety stock requirement is set equal to 10 percent of the total quantity of all products transferred from this plant to all warehouses.

Table 5-3: Unit production and unit inventory holding cost of product *i* in plan *j**

Plant	Production (RMU/i)								Inventory (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
j_1	2.80	3.00	3.10	2.55	2.10	2.80	3.10	2.70	0.38	0.25	0.25	0.29	0.29	0.43	0.24	0.19
j_2	2.95	3.00	2.95	2.80	3.20	2.90	2.25	2.40	0.40	0.26	0.25	0.30	0.28	0.53	0.26	0.20

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Table 5-4: Unit transportation cost between plant *j* and warehouse *m**

Plant to warehouse	Product (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
j_1-m_1	0.10	0.05	0.10	0.15	0.10	0.05	0.05	0.05
j_1-m_2	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
j_1-m_3	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
j_2-m_1	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
j_2-m_2	0.05	0.05	0.05	0.05	0.15	0.10	0.15	0.15
j_2-m_3	1.25	1.05	1.10	1.10	1.15	1.00	1.10	1.15

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Warehouses

Details on material handling and storage costs are presented in Table 5-5. All warehouses are assumed to have a maximum and a minimum product handling capacity that is shown in Table 5-6 along with their fixed infrastructure cost. The coefficient relating the capacity of a warehouse to the throughput of each product handled is taken to be one percent ($\gamma_{im} = 0.01$).

Table 5-5: Material handling & inventory holding costs of warehouse *m**

Warehouse	Material handling (C_{im}^{WH}) (RMU/i)								Inventory holding (C_{ij}^{I}) (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
m_1	0.34	0.58	0.36	0.42	0.33	0.34	0.84	0.77	0.28	0.38	0.32	0.54	0.46	0.51	0.41	0.46
m_2	0.45	0.40	0.52	0.39	0.33	0.44	0.86	0.68	0.38	0.37	0.37	0.44	0.54	0.47	0.38	0.41
m_3	0.78	0.62	0.70	0.64	0.44	0.59	0.80	0.85	0.50	0.50	0.30	0.43	0.21	0.38	0.35	0.54

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Table 5-6: Infrastructure cost & capacities of warehouse *m**

Warehouse	Infrastructure (C_m^W) (RMU)	Maximum capacity (W_m^{max}) (i/y)	Minimum capacity (W_m^{min}) (i/y)
m_1	42,500	17,000	1900
m_2	37,000	16,000	2200
m_3	35,000	20,000	2500

* There is no difference among several scenarios and time periods.
Note: i/y means items per year.

Table 5-7: Unit transportation cost between warehouse *m* and distribution centre *k**

Warehouse to distribution centre	Product (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
m_1-k_1	0.10	0.05	0.10	0.15	0.10	0.05	0.05	0.05
m_1-k_2	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
m_1-k_3	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
m_1-k_4	0.40	0.35	0.45	0.40	0.40	0.45	0.45	0.45
m_2-k_1	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
m_2-k_2	0.05	0.05	0.05	0.05	0.15	0.10	0.15	0.15
m_2-k_3	1.25	1.05	1.10	1.10	1.15	1.00	1.10	1.15
m_2-k_4	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
m_3-k_1	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
m_3-k_2	1.25	1.05	1.10	1.10	1.15	1.00	1.10	1.15
m_3-k_3	0.05	0.10	0.10	0.05	0.10	0.05	0.05	0.10
m_3-k_4	0.45	0.45	0.40	0.45	0.40	0.45	0.50	0.40

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Table 5-7 presents the unit transportation cost from potential warehouses to distribution centres. Warehouses hold no initial inventory and the safety stock requirement is set equal to five percent of the total quantity of all products transferred from this warehouse to all distribution centres. The minimum quantity of products that can practically and economically be transferred to each distribution centre is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Distribution centres

Details on material handling and storage costs are presented in Table 5-8. All distribution centres are assumed to have a maximum and a minimum product handling capacity that is shown in Table 5-9 along with their fixed infrastructure cost. The coefficient relating the capacity of a distribution centre to the throughput of each product handled is taken to be one percent ($\gamma_{ik} = 0.01$).

Table 5-8: Material handling & inventory holding costs of distribution centre *k**

Warehouse	Material handling $\left(C_{ik}^{DH}\right)$ (RMU/i)								Inventory holding $\left(C_{ik}^{I}\right)$ (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
k_1	0.45	0.42	0.72	0.72	0.60	0.58	0.42	0.79	0.43	0.48	0.50	0.50	0.38	0.30	0.38	0.46
k_2	0.64	0.58	0.60	0.64	0.55	0.50	0.44	0.78	0.50	0.51	0.50	0.45	0.41	0.33	0.38	0.48
k_3	0.82	0.78	0.46	0.62	0.75	0.88	0.78	0.64	0.33	0.22	0.30	0.41	0.46	0.37	0.50	0.49
k_4	0.45	0.65	0.46	0.65	0.90	0.56	0.76	0.96	0.48	0.33	0.33	0.44	0.29	0.48	0.50	0.35

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Table 5-9: Infrastructure cost & capacities of distribution centre *k**

Distribution centre	Infrastructure $\left(C_k^D\right)$ (RMU)	Maximum capacity $\left(D_k^{max}\right)$ (i/y)	Minimum capacity $\left(D_k^{min}\right)$ (i/y)
k_1	40,000	22,000	1500
k_2	42,500	20,000	1900
k_3	45,000	27,000	1100
k_4	37,000	27,000	1300

* There is no difference among several scenarios and time periods.
Note: i/y means items per year.

In Table 5-10 the unit transportation cost from potential distribution centres to customer zones, is presented. Distribution centres hold no initial inventory and the safety stock requirement is set equal to one percent of the total quantity of all products transferred from this distribution centre to all customer zones. The minimum quantity of products that can practically and economically be transferred to each customer zone is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

Customer zones

For the fist time period product demands for the eight customer zones are given in Table 5-11. In the next time period economic uncertainty is becoming more discernible so three predictions are made, as shown in Tables 5-12 to 5-14. In a similar manner, in the third time period three predictions are made for each one of the previous' period predictions (see Tables 5-15 to 5-23). Overall, we consider nine distinct scenarios organised in an analogous tree structure of the type shown in Figure 5-2.

Table 5-10: Unit transportation cost between distribution centre *k* and customer zone *l**

Distribution centre to customer zone	Product (RMU/i)							
	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
k_1-l_1	0.10	0.05	0.10	0.15	0.10	0.05	0.05	0.05
k_1-l_2	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
k_1-l_3	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
k_1-l_4	0.55	0.60	0.55	0.55	0.50	0.60	0.55	0.55
k_1-l_5	0.65	0.60	0.60	0.65	0.60	0.60	0.65	0.55
k_1-l_6	0.70	0.70	0.70	0.75	0.65	0.65	0.65	0.70
k_1-l_7	0.45	0.45	0.45	0.50	0.50	0.50	0.45	0.45
k_1-l_8	0.65	0.65	0.65	0.65	0.60	0.60	0.60	0.60
k_2-l_1	0.75	0.70	0.60	0.65	0.65	0.60	0.70	0.65
k_2-l_2	0.05	0.05	0.05	0.05	0.15	0.10	0.15	0.15
k_2-l_3	1.25	1.05	1.10	1.10	1.15	1.00	1.10	1.15
k_2-l_4	1.05	0.95	1.00	1.00	0.95	1.05	1.10	1.00
k_2-l_5	1.00	1.05	1.05	1.05	1.05	1.00	0.95	1.00
k_2-l_6	0.60	0.60	0.65	0.50	0.50	0.60	0.60	0.65
k_2-l_7	0.60	0.60	0.60	0.60	0.65	0.60	0.65	0.65
k_2-l_8	0.70	0.75	0.65	0.70	0.70	0.70	0.70	0.65
k_3-l_1	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
k_3-l_2	1.25	1.05	1.10	1.10	1.15	1.00	1.10	1.15
k_3-l_3	0.05	0.10	0.10	0.05	0.10	0.05	0.05	0.10
k_3-l_4	0.60	0.60	0.65	0.50	0.50	0.60	0.60	0.65
k_3-l_5	0.60	0.60	0.65	0.50	0.50	0.60	0.60	0.65
k_3-l_6	0.90	0.90	0.95	0.95	0.95	0.90	0.90	0.90
k_3-l_7	1.00	1.00	1.00	1.05	0.95	0.95	1.00	1.00
k_3-l_8	0.80	0.75	0.75	0.80	0.80	0.75	0.75	0.75
k_4-l_1	0.40	0.35	0.45	0.40	0.40	0.45	0.45	0.45
k_4-l_2	0.80	0.75	0.75	0.70	0.75	0.80	0.75	0.75
k_4-l_3	0.45	0.45	0.40	0.45	0.40	0.45	0.50	0.40
k_4-l_4	0.40	0.35	0.40	0.40	0.45	0.35	0.35	0.40
k_4-l_5	0.40	0.35	0.35	0.35	0.35	0.35	0.35	0.35
k_4-l_6	0.60	0.60	0.55	0.55	0.50	0.60	0.55	0.55
k_4-l_7	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90
k_4-l_8	0.50	0.50	0.50	0.55	0.50	0.55	0.50	0.55

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Table 5-11: Demand for product *i* from customer zone *l* over the first period (all scenarios)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	440	500	610	480	370	550	560	290
i_2	550	600	570	320	230	360	210	310
i_3	620	390	530	310	230	390	290	300
i_4	430	360	720	220	290	250	370	600
i_5	520	440	380	190	460	180	320	540
i_6	370	530	250	580	540	330	190	580
i_7	450	470	480	310	410	450	170	450
i_8	440	310	490	660	270	460	160	450

Note: i/y means items per year.

Table 5-12: Demand for product *i* from customer zone *l* over the second period (scenario 1-3)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	484	550	671	528	407	605	616	319
i_2	605	660	627	352	253	396	231	341
i_3	682	429	583	341	253	429	319	330
i_4	473	396	792	242	319	275	407	660
i_5	572	484	418	209	506	198	352	594
i_6	407	583	275	638	594	363	209	638
i_7	495	517	528	341	451	495	187	495
i_8	484	341	539	726	297	506	176	495

Note: i/y means items per year.

Table 5-13: Demand for product *i* from customer zone *l* over the second period (scenario 4-6)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	440	500	610	480	370	550	560	290
i_2	550	600	570	320	230	360	210	310
i_3	620	390	530	310	230	390	290	300
i_4	430	360	720	220	290	250	370	600
i_5	520	440	380	190	460	180	320	540
i_6	370	530	250	580	540	330	190	580
i_7	450	470	480	310	410	450	170	450
i_8	440	310	490	660	270	460	160	450

Note: i/y means items per year.

Table 5-14: Demand for product *i* from customer zone *l* over the second period (scenario 7-9)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	396	450	549	432	333	495	504	261
i_2	495	540	513	288	207	324	189	279
i_3	558	351	477	279	207	351	261	270
i_4	387	324	648	198	261	225	333	540
i_5	468	396	342	171	414	162	288	486
i_6	333	477	225	522	486	297	171	522
i_7	405	423	432	279	369	405	153	405
i_8	396	279	441	594	243	414	144	405

Note: i/y means items per year.

Table 5-15: Demand for product *i* from customer zone *l* over the third period (scenario 1)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	506	575	702	552	426	633	644	334
i_2	633	690	656	368	265	414	242	357
i_3	713	449	610	357	265	449	334	345
i_4	495	414	828	253	334	288	426	690
i_5	598	506	437	219	529	207	368	621
i_6	426	610	288	667	621	380	219	667
i_7	518	541	552	357	472	518	196	518
i_8	506	357	564	759	311	529	184	518

Note: i/y means items per year.

Table 5-16: Demand for product *i* from customer zone *l* over the third period (scenario 2)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	484	550	671	528	407	605	616	319
i_2	605	660	627	352	253	396	231	341
i_3	682	429	583	341	253	429	319	330
i_4	473	396	792	242	319	275	407	660
i_5	572	484	418	209	506	198	352	594
i_6	407	583	275	638	594	363	209	638
i_7	495	517	528	341	451	495	187	495
i_8	484	341	539	726	297	506	176	495

Note: i/y means items per year.

Table 5-17: Demand for product *i* from customer zone *l* over the third period (scenario 3)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	463	526	641	505	389	578	589	305
i_2	578	631	599	337	242	379	221	326
i_3	652	410	557	326	242	410	305	316
i_4	452	379	757	232	305	263	389	631
i_5	547	463	400	200	484	190	337	568
i_6	389	557	263	610	568	347	200	610
i_7	473	494	505	326	431	473	179	473
i_8	463	326	515	694	284	484	169	473

Note: i/y means items per year.

Table 5-18: Demand for product *i* from customer zone *l* over the third period (scenario 4)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	460	523	638	502	387	575	586	304
i_2	575	627	596	335	241	377	220	324
i_3	648	408	554	324	241	408	304	314
i_4	450	377	753	230	304	262	387	627
i_5	544	460	398	199	481	189	335	565
i_6	387	554	262	607	565	345	199	607
i_7	471	492	502	324	429	471	178	471
i_8	460	324	513	690	283	481	168	471

Note: i/y means items per year.

Table 5-19: Demand for product *i* from customer zone *l* over the third period (scenario 5)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	440	500	610	480	370	550	560	290
i_2	550	600	570	320	230	360	210	310
i_3	620	390	530	310	230	390	290	300
i_4	430	360	720	220	290	250	370	600
i_5	520	440	380	190	460	180	320	540
i_6	370	530	250	580	540	330	190	580
i_7	450	470	480	310	410	450	170	450
i_8	440	310	490	660	270	460	160	450

Note: i/y means items per year.

Table 5-20: Demand for product *i* from customer zone *l* over the third period (scenario 6)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	421	478	583	459	354	526	535	277
i_2	526	573	545	306	220	344	201	297
i_3	593	373	507	297	220	373	277	287
i_4	411	344	688	211	277	239	354	573
i_5	497	421	363	182	440	172	306	516
i_6	354	507	239	554	516	316	182	554
i_7	430	449	459	297	392	430	163	430
i_8	421	297	468	631	258	440	153	430

Note: i/y means items per year.

Table 5-21: Demand for product *i* from customer zone *l* over the third period (scenario 7)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	414	471	574	452	348	518	527	273
i_2	518	565	537	301	217	339	198	292
i_3	584	367	499	292	217	367	273	283
i_4	405	339	678	207	273	236	348	565
i_5	490	414	358	179	433	170	301	508
i_6	348	499	236	546	508	311	179	546
i_7	424	443	452	292	386	424	160	424
i_8	414	292	461	621	254	433	151	424

Note: i/y means items per year.

Table 5-22: Demand for product *i* from customer zone *l* over the third period (scenario 8)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	396	450	549	432	333	495	504	261
i_2	495	540	513	288	207	324	189	279
i_3	558	351	477	279	207	351	261	270
i_4	387	324	648	198	261	225	333	540
i_5	468	396	342	171	414	162	288	486
i_6	333	477	225	522	486	297	171	522
i_7	405	423	432	279	369	405	153	405
i_8	396	279	441	594	243	414	144	405

Note: i/y means items per year.

Table 5-23: Demand for product *i* from customer zone *l* over the third period (scenario 9)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	379	430	525	413	319	473	482	250
i_2	473	516	490	276	198	310	181	267
i_3	533	336	456	267	198	336	250	258
i_4	370	310	619	190	250	215	319	516
i_5	447	379	327	164	396	155	276	465
i_6	319	456	215	499	465	284	164	499
i_7	387	404	413	267	353	387	147	387
i_8	379	267	422	568	233	396	138	387

Note: i/y means items per year.

In Table 5-24 the price of each product in each customer zone is presented and as the company implements a customary pricing policy there is no difference among several scenarios and time periods.

Table 5-24: Price for product *i* from customer zone *l***

Product	Customer zone (RMU/i)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	9.14	9.39	7.95	8.71	9.14	9.56	9.65	8.90
i_2	8.29	8.08	8.63	8.71	8.37	8.80	8.50	8.88
i_3	10.07	9.22	9.07	9.22	8.12	10.68	10.77	9.22
i_4	8.12	10.68	9.75	9.75	9.93	10.66	10.49	10.83
i_5	10.84	11.26	11.43	11.71	10.67	10.17	11.60	10.86
i_6	10.95	11.90	9.65	10.94	10.20	10.16	9.16	10.94
i_7	10.44	9.56	10.52	11.26	12.37	10.52	9.59	10.41
i_8	11.26	11.42	10.96	11.60	11.79	11.80	11.88	10.86

* There is no difference among several scenarios and time periods.
Note: RMU/i means RMU per item.

Financial operation

The balance sheet, at the beginning of the planning horizon, is presented in Table 5-25. The company depreciates its assets with the straight line method, instead of accelerated method or production method, and thus there is no difference from year to year in the depreciation rates which are for existing assets 5.00% per year and for new assets 2.50% per year. The historical cost of existing fixed assets is 210,000 RMU. Moreover, the tax rate is 30.00% per year, the selling, general, and administrative expenses are estimated at 25,000 RMU per year, and the beta coefficient is equal to unity. The nominal value of outstanding stocks is 7.00 RMU per stock while their market value is 7.75 RMU per stock.

Table 5-25: Balance sheet at the beginning of planning period

Account	RMU	Account	RMU
Fixed assets	**170,000**	**Equity**	**130,000**
Tangible assets	170,000	Contributed capital	80,000
Intangible assets	0	Retained earnings	50,000
Current assets	**70,000**	**Debt**	**110,000**
Inventory	12,032	Short-term liabilities	45,000
Accounts receivable	28,000	Long-term liabilities	65,000
Cash	29,968		
TOTAL ASSETS	***240,000***	***TOTAL EQUITY & DEBT***	***240,000***

The six out of seven parameters that express into a large extend the economic uncertainty are presented in Tables 5-26 to 5-28. Product demand, which is the seventh parameter, has been presented in Section 5.4.1.4. These parameters have been estimated by company's managers and are in accordance with the scenario tree structure presented in Fig. 3. The probabilities of scenarios are ($\psi_1 = \psi_3 = \psi_7 = \psi_9 = 0.0625$), ($\psi_2 = \psi_4 = \psi_6 = \psi_8 = 0.1250$), and ($\psi_5 = 0.250$).

Table 5-26: Financial parameters for economic scenario *s* over the first period

Financial parameter	Scenario (%)								
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
Short-term interest rate ($\mathrm{STR}_t^{[s]}$)	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Long-term interest rate ($\mathrm{LTR}_t^{[s]}$)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Risk-free rate of interest (${r_f}_t^{[s]}$)	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Expected return of the market (${r_m}_t^{[s]}$)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Underwriting cost ($\mathrm{UNDC}_t^{[s]}$)	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Market liquidity ($\mathrm{CFP}_t^{[s]}$)	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00

Table 5-27: Financial parameters for economic scenario *s* over the second period

Financial parameter	Scenario (%)								
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
Short-term interest rate ($\mathrm{STR}_t^{[s]}$)	5.60	5.60	5.60	7.00	7.00	7.00	8.40	8.40	8.40
Long-term interest rate ($\mathrm{LTR}_t^{[s]}$)	3.00	3.00	3.00	4.00	4.00	4.00	5.00	5.00	5.00
Risk-free rate of interest (${r_f}_t^{[s]}$)	2.00	2.00	2.00	2.50	2.50	2.50	3.00	3.00	3.00
Expected return of the market (${r_m}_t^{[s]}$)	6.00	6.00	6.00	5.00	5.00	5.00	4.00	4.00	4.00
Underwriting cost ($\mathrm{UNDC}_t^{[s]}$)	2.40	2.40	2.40	3.25	3.25	3.25	5.40	5.40	5.40
Market liquidity ($\mathrm{CFP}_t^{[s]}$)	75.00	75.00	75.00	60.00	60.00	60.00	45.00	45.00	45.00

Table 5-28: Financial parameters for economic scenario *s* over the third period

Financial parameter	Scenario (%)								
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
Short-term interest rate ($\mathrm{STR}_t^{[s]}$)	5.30	5.60	5.90	6.70	7.00	7.40	8.00	8.40	8.80
Long-term interest rate ($\mathrm{LTR}_t^{[s]}$)	2.70	3.00	3.30	3.60	4.00	4.40	4.50	5.00	5.50
Risk-free rate of interest (${\mathrm{r}_f}_t^{[s]}$)	1.90	2.00	2.10	2.40	2.50	2.60	2.90	3.00	3.20
Expected return of the market (${\mathrm{r}_m}_t^{[s]}$)	6.30	6.00	5.70	5.30	5.00	4.80	4.20	4.00	3.80
Underwriting cost ($\mathrm{UNDC}_t^{[s]}$)	2.30	2.40	3.00	3.10	3.25	4.10	5.10	5.40	6.80
Market liquidity ($\mathrm{CFP}_t^{[s]}$)	82.50	75.00	67.50	66.00	60.00	54.00	49.50	45.00	40.50

5.4.2 Implementation

The model M3 was solved with the DICOPT solver (NLP: CONOPT and MIP: CPLEX 11.2.0) incorporated in GAMS 22.9 software (Rosenthal, 2008). The model consisted of 21,546 constrains, 14,010 continuous variables, and 51 discrete variables. Runs were performed on a Pentium R Dual Core with 2.50GHz CPU and 3GB RAM. On average the solutions were obtained at approximately 1400 CPU seconds with minimum time 746 CPU seconds and maximum 2434 CPU seconds and all with 0% integrality gap.

5.4.2.1 Results

Figure 5-4 shows the Pareto efficient frontier for Altman's Z-score versus EVA™. From this figure the trade-offs between financial performance and credit solvency are evident. Each point in this frontier corresponds to a different optimal SCN configuration which, based on decision maker's preferences, could be selected.

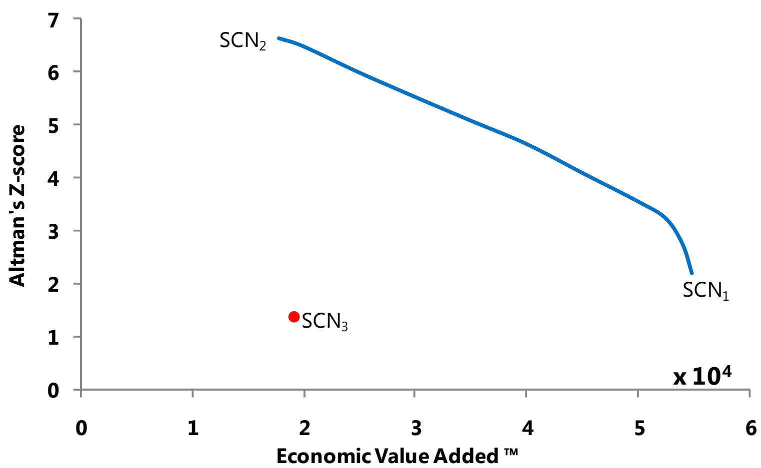


Figure 5-4: Pareto efficient frontier from model M3

In order to get a more detailed picture on M3 model's decision mechanism, two points were selected and their SCNs are presented in Figures 5-5 and 5-6. Figure 5-5 presents the optimal configuration of the network that creates the maximum EVA™ while ignoring Altman's Z-score (SCN_1). On the other hand, Figure 5-6 presents the optimal configuration of the network that scores the maximum Altman's Z-score while ignoring EVA™ (SCN_2).

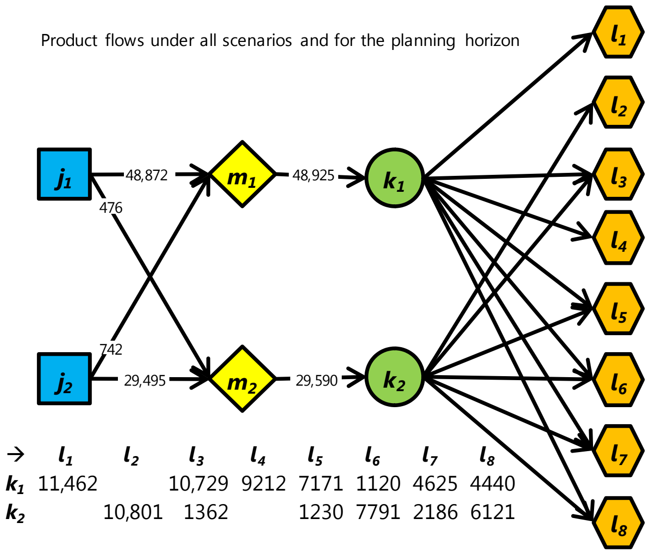


Figure 5-5: Optimal configuration from model M3 of SCN_1 (EVA: 54,839 & Z-score: 2.18)

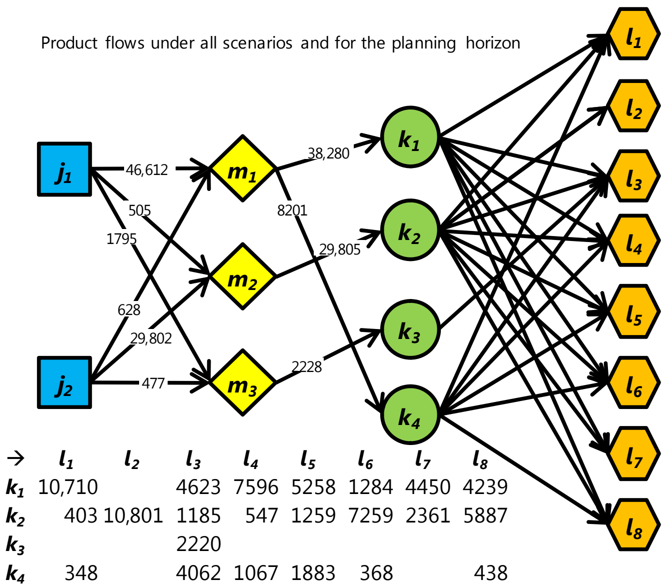


Figure 5-6: Optimal configuration from model M3 of SCN_2 (EVA: 17,844 & Z-score: 6.64)

SCN_1 is leaner as it establishes two out of three potential warehouses and two out of four potential distribution centres whereas SCN_2 is rich and complicated as it establishes all potential warehouses and distribution centres and many transportation connections.

Figures 5-7 to 5-10 present a comparative analysis of the two selected optimal SCN configurations. Comparing SCN_1 with SCN_2, it is evident from Figure 5-7 that both configurations have almost the same operational costs except the infrastructure cost. SCN_2 has an increased infrastructure cost as it selects more warehouses and more distribution centres.

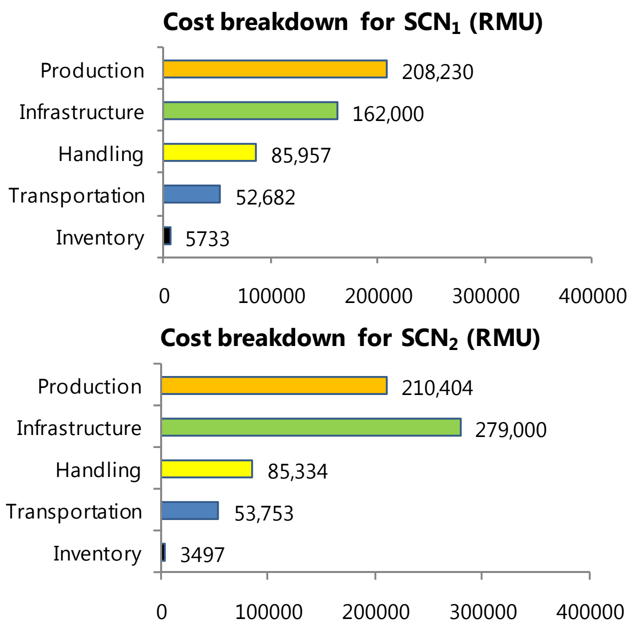


Figure 5-7: Comparison of operational costs between SCN_1 and SCN_2

Figure 5-8 shows the inventories, under all scenarios and at the end of each time period, in both SCN's. In SCN_1 the trend of inventories shows a decrease during the planning horizon, although inventories in distribution centres at the end of the second time period are high. In SCN_2 the trend of inventories also shows a decrease during the planning horizon with inventories in the third warehouse and in all distribution centres kept extremely low in all time periods.

For both SCN's, Figure 5-9 shows the assets structure while Figure 5-10 shows the capital structure. In SCN_1 the assets structure illustrates an increase in fixed assets attributed solely to the establishment of two warehouses and two distribution centres and an increase in current assets attributed to cash and receivable accounts generated from the transfer of earnings from the income statement to the balance sheet, and to inventories stocked. Regarding, SCN_2 the assets structure illustrates an increase in fixed assets attributed solely to the establishment of three warehouses and four distribution centres and an increase in current assets attributed to a large extend to the cash generated from new issued stocks for working capital investment purposes, to cash and receivable accounts generated from the transfer of earnings from the income statement to the balance sheet, and to inventories stocked.

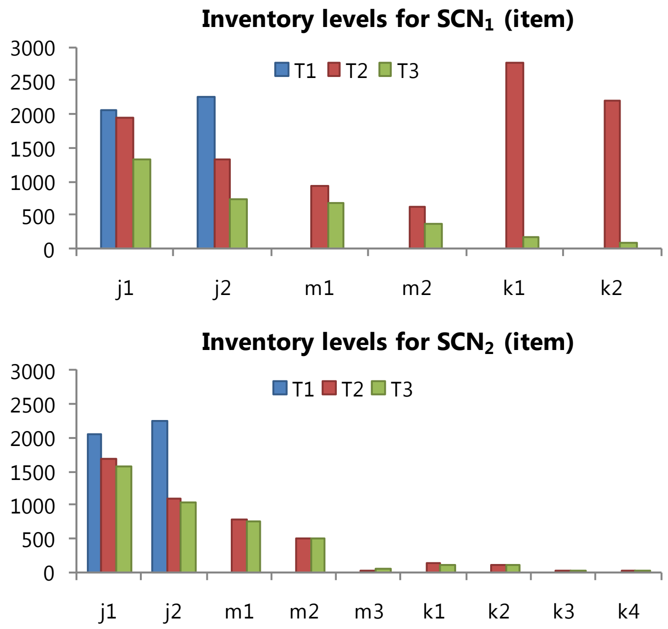


Figure 5-8: Comparison of inventory levels under all scenarios between SCN_1 and SCN_2

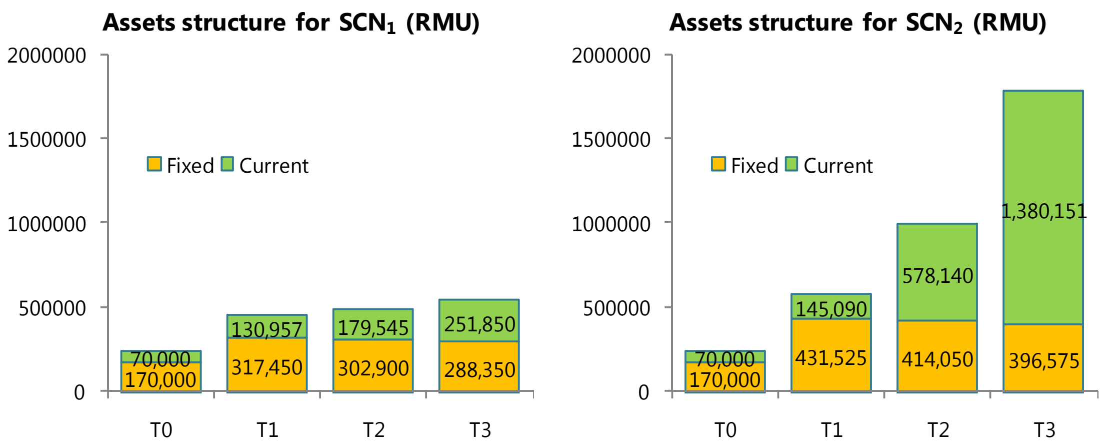


Figure 5-9: Comparison of assets' structure between SCN_1 and SCN_2

The capital structure, in SCN_1, illustrates an increase in debt attributed solely to the financing of fixed assets and an increase in equity attributed solely to the transfer of earnings from the income statement to the balance sheet. In SCN_2, the capital structure illustrates stability in debt and an increase in equity attributed to a large percent to new issued stocks for fixed assets investment purposes for the first period and to new issued stocks for working capital investment purposes for the other periods, and to the transfer of earnings from the income statement to the balance sheet.

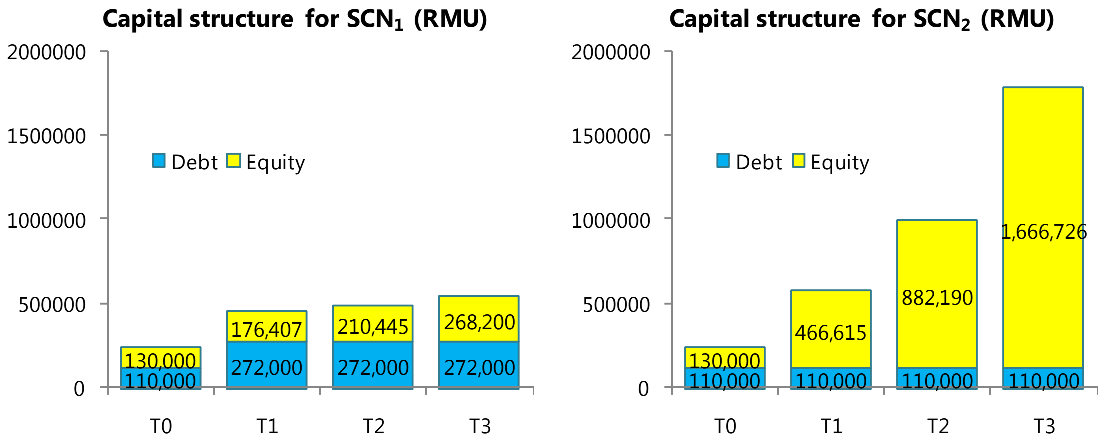


Figure 5-10: Comparison of capital structure between SCN_1 and SCN_2

These two extreme SCNs provide insights into the trade-offs between financial performance and credit solvency. In specific, both models have the same net sales as the model assumes that demand should be satisfied. Going from net sales to net operating profits after taxes various expenses are subtracted. However, as mentioned earlier, production, handling, inventory, and transportation costs are quite similar. Hence, the difference is on depreciation and fixes assets financing cost (interest paid or underwriting cost).

SCN_1 is focused on maximising EVA™ and driven by this objective it maximises NOPAT and minimises WACC and invested capital, respectively. By selecting only two warehouses and two distribution centres it has lower depreciation and lower invested capital. Moreover, by selecting to finance the establishment of these warehouses and distribution centres with debt, instead of equity, it has lower WACC (c.f. Figure 5-11) and lower tax bill due to more interest paid. Interest cost is a tax deductible expense because the amount a company pays in interest (on debt) is deducted from its earnings before calculating the tax it must pay. Its tax bill is therefore reduced, the greater the amount of interest that is payable. In this sense, having debt rather than equity 'shields' a firm from part of its tax bill. However, debt financing affects the fourth constituent ratio of Altman's Z-score, namely, market value of equity to book value of total liabilities, resulting in a low total solvency score.

On the other hand, SCN_2 is focused on maximising Altman's Z-score and driven by this objective it maximises, whenever possible, all constituent ratios' nominators and minimises all constituent ratios' denominators. By selecting all available warehouses and distribution centres it has lower NOPAT, due to higher depreciation, and higher invested capital. Moreover, by selecting to finance the establishment of these warehouses and distribution centres with equity, instead of debt, it has higher WACC (c.f. Figure 5-11) and all these conditions resulting in a low EVA™. However, equity financing affects, in an analogous manner mentioned earlier, the fourth and the first constituent ratio of Altman's Z-score. In specific, during the first period the new issued stocks for fixed assets investment purposes increases the market value of equity with book value of total liabilities been stable. During the other periods, the new issued stocks for working capital investment purposes increases both market value of equity and working capital through cash flows with short-term liabilities been stable. These increases in equity increase total assets as the basic equation of the balance sheet should be satisfied. However, the combined effect resulting in a high total solvency score.

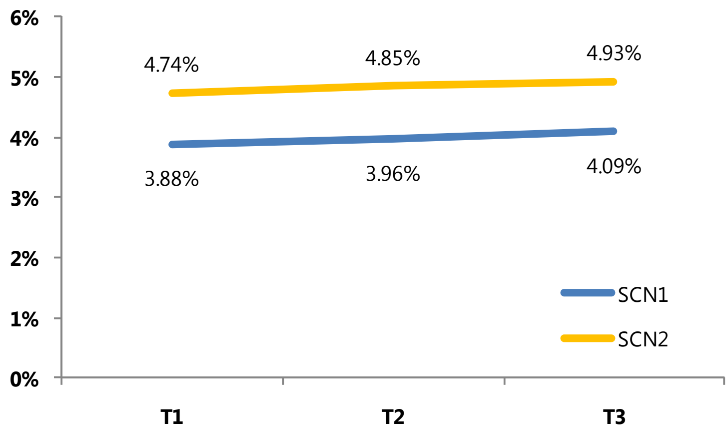


Figure 5-11: WACC comparison between SCN_1 and SCN_2

In interpreting the case study results, a logic question arises. Why to establish, in the case of SCN_2, so many warehouses and distribution centres if demand is satisfied with less? This is the main viewpoint difference between SCN managers and financial managers. A myopic approach considers these warehouses and distribution centres as redundant expenses that diminishing profits. However, this approach fails to perceive that these warehouses and distribution centres are fixed assets of the company and as such they might have a market value higher that the value shown in the balance sheet. Under favourable conditions in the real estate market these fixed assets could be sold or sold and leased back resulting in excessive liquidity for the company. Moreover, these fixed assets provide "depreciation shield" advantages and revaluation gains.

5.4.3 Comparison with a cost minimisation model

Simultaneous consideration of financial performance and credit solvency is the main novelty of our model M3. Hence, a comparison with a cost minimisation model M3', which ignores these pillars of financial attractiveness and focuses on minimising operational costs, deemed worthy in further evaluating the proposed model M3.

This model (M3') aimed at minimising the total expected value of the cost of the four operational costs of the SCN, namely, production cost, handling cost, transportation cost, and inventory cost, along with the total infrastructure cost while the EVA™ and the Altman's Z-score were calculated a posteriori, rather than optimised. Model M3' has the following mathematical representation:

$$\mathrm{OBJ}^{3'}: \min \sum_{t}^{NT} \sum_{s}^{NS} \psi_s \Bigg[\sum_{i,j} \mathrm{C}_{ij}^{P}\, \mathrm{P}_{ijt}^{[s]} + \sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]} + \sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]} + \sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]}$$
$$+ \sum_{i,m} \mathrm{C}_{im}^{WH} \left(\sum_{j} \mathrm{Q}_{ijmt}^{[s]} \right) + \sum_{i,k} \mathrm{C}_{ik}^{DH} \left(\sum_{m} \mathrm{Q}_{imkt}^{[s]} \right) + \sum_{i,j} \mathrm{C}_{ij}^{I} \frac{\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{ij,t-1}^{[s]}}{2}$$
$$+ \sum_{i,m} \mathrm{C}_{im}^{I} \frac{\mathrm{I}_{imt}^{[s]} + \mathrm{I}_{im,t-1}^{[s]}}{2} + \sum_{i,k} \mathrm{C}_{ik}^{I} \frac{\mathrm{I}_{ikt}^{[s]} + \mathrm{I}_{ik,t-1}^{[s]}}{2} \Bigg] + \sum_{m} \mathrm{C}_{m}^{WF}\, \mathrm{PW}_m + \sum_{k} \mathrm{C}_{k}^{DF} \mathrm{PDC}_k$$

subject to constraints (3.1)–(3.11), (3.15)–(3.24), (3.28)–(3.36), (4.1), and (5.1)–(5.61).

We solve again the MINLP problem M3', using the real case study data presented in Section 5.4, and the results are presented in Figures 5-11 and 5-12 while for better comparison illustrations a point labelled SCN_3 was introduced in Figure 5-4.

The cost driven model selects only one warehouse and one distribution centre and thus infrastructure costs are decreased and transportation cost are increased. But the essential difference is in financial performance and credit solvency. The model not only created very low EVA™ but also its solvency fails into the default area (Z-score < 1.81).

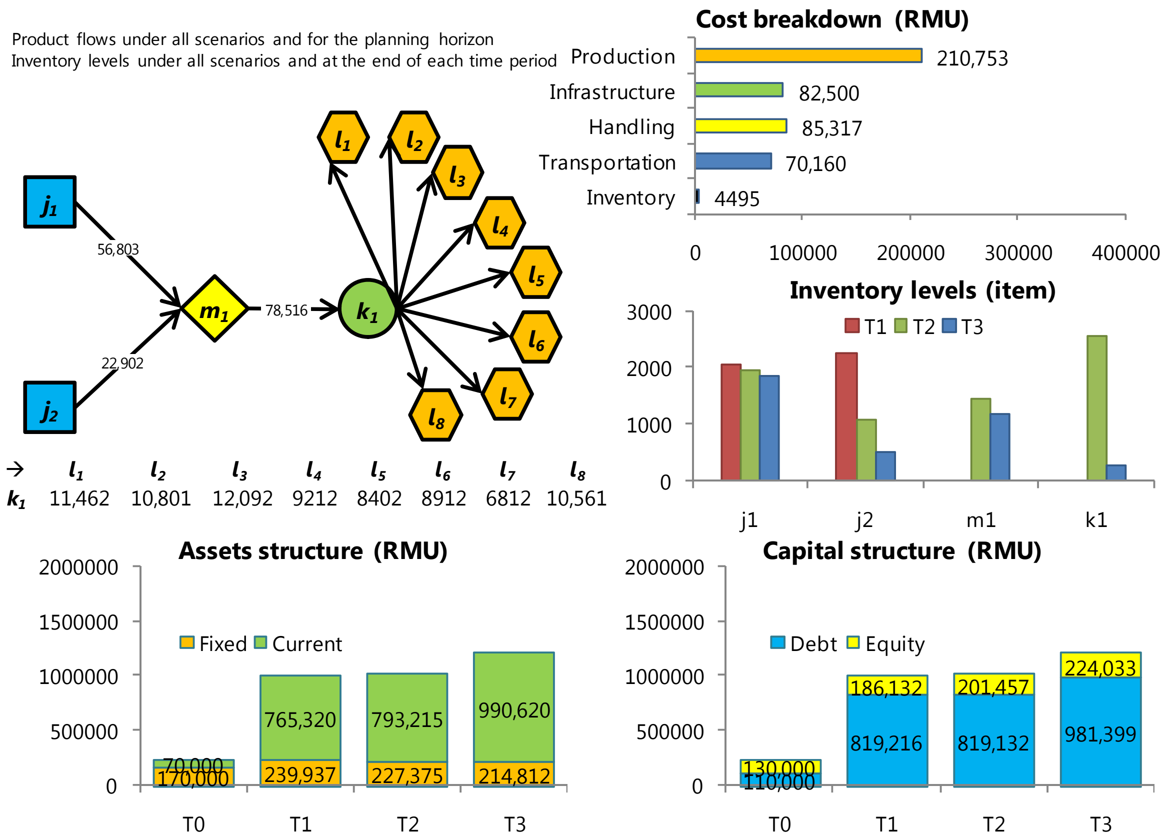


Figure 5-12: Optimal configuration from model M3′ of SCN_3 (EVA: 19,311 & Z-score: 1.37)

5.5 Concluding remarks

In this chapter, our research effort was motivated and directed by the impact of economic uncertainty on SCNs' financial status. A viable and healthy financial status provides the necessary funds in a SCN. These funds are not in abundance and are accessed if a company has satisfactory financial performance and credit solvency. However, these two desirable conditions are not always moving towards the same direction and business managers should find a balance between them.

The proposed moMINLP SCN design model M3 considers the aforementioned factors via two popular indexes, namely EVA™ AND Altman's Z-score, and handles economic uncertainty, inherent in financial operations, through the scenario tree approach. The model was evaluated in a real small-scale case study and the generated Pareto efficient frontier demonstrated unambiguously the trade-offs between financial performance and credit solvency. Moreover, we illustrate the superiority, in terms of financial performance and credit solvency, of the proposed model (M3) against a cost minimisation counterpart model (M3′). Model M3′, driven purely by cost objectives, resulted in a lean and costless SCN but failed to consider the financial attractiveness.

This Pareto efficient frontier provides decision maker a portfolio of alternative optimal SCNs that could be selected based on company's strategic orientation, competitive landscape, and business life cycle. Moreover, the model supports SCN managers in negotiations with financial managers because it uses a "common language" between them and promotes constructive cooperation between them. As the final acceptance of an investment project is mainly decided by financial managers, a capital budgeting proposal, such as the establishment/restructure of the company's SCN, employing financial figures and indexes and making clear to these managers the effect of this project on financial performance and credit solvency, has more possibilities to be accepted. In addition, the model requires active participation of financial managers in economic uncertainty modelling via the estimation of financial parameters and this way the possibilities of acceptance are increased.

Although the present SCN design contribution brings to the forefront the trade-offs between financial performance and credit solvency, under economic uncertainty, a potential limitation should be noted. In specific, the proposed model was evaluated in a real small-scale case study and the computational effort was reasonable. However, due to the nonlinear nature of the model and due to the scenario tree approach method, which explodes rapidly in size as the number of time periods grows, the computational requirements are high as the size of the problem increases. The solutions of large-scale problems deserve further research where specific solution techniques might be necessary.

Finally, future research might enrich our model with risk exposure methodologies, such as value at risk (VaR), downside risk, and stress tests, just to name a few. Other avenues worth for further study might focus on modelling advanced financial management aspects such as "sale and leaseback" of fixed assets and commodity forward contracts.

CHAPTER 6

Integration of sale leaseback in the optimal design of SCNs

6.1 Introduction

SCN design is a strategic procedure that designs network's infrastructure and concerns long-term investments that undertake huge amounts of capitals. Under these conditions, sizable investment in long-term assets, the SCN design is a project included in a company's capital budgeting process.

Capital budgeting is the process of evaluating and selecting long-term investments that are consistent with the firm's goal of maximising owner wealth. Firms typically make a variety of long-term investments, but the most common for the manufacturing firm is in fixed assets, which include property (land), plant, and equipment. These assets, often referred to as earning assets, generally provide the basis for the firm's earning power and value (Gitman, 2006).

All projects that maximise the shareholder value should be accepted. However, capital (whether debt or equity) is a very limited resource and should be allocated among the best investment alternatives. In reality, managers are facing limited sources of capital and should decide carefully whether a particular project contribute more to the value of the firm. In this competitive evaluation among mutually exclusive projects, cost oriented indicators, such as incremental cash outflow and resulting subsequent inflows, have the leading role.

The SCN design/redesign/retrofitting project could gain a comparative advantage, against other projects, by employing advance financial management methods that add more quantitative and qualitative information regarding shareholder value maximisation. One such technique is the sale and leaseback (SLB) of fixed assets that in quantitative terms provides unearned profits and in qualitative terms improves liquidity and strengthens credit solvency.

This chapter aims to enrich the SCN design literature by introducing a robust mixed integer non linear programming (MINLP) SCN design model that integrates the SLB technique with SCN design decisions. In particular, the proposed model aimed at finding the optimal SCN configuration, under uncertainty in product demand and in real estate market, driven by two financial objectives, namely, NOPAT and unearned profit on SLB and restricted by various structural and operational constraints.

Section 6.2 presents the theoretical and methodological background of SLB agreements followed by a mathematical programming formulation in Section 6.3. The applicability of the developed model is illustrated in Section 6.4 by using a small-scale real case study. Finally, concluding remarks are drawn in Section 6.5.

6.2 Financial considerations

6.2.1 Sale and leaseback (SLB)

Although SLB is not a new concept in financial management, since the mid-1990s the number, value, and industry dispersion of these deals has been following an accelerating trend (Barris, 2002). Many studies have presented empirical evidence supporting that SLB is a value-increasing transaction (Slovin, Sushka, & Polonchek, 1990) which provides wealth gains superior to debt financing (Rutherford, 1990), optimises company's claims to real estate (Fisher, 2004), improves liquidity that is directed either to finance expansion or to pay off existing creditors (Ben-David, 2005), reveals hidden value of company's assets (Grönlund, Louko, & Vaihekoski, 2008), and achieves capital and supported business objectives (Morris, 2010).

A SLB transaction is one involving the sale of property by the owner (seller-lessee), who simultaneously leases it back from the new owner (buyer-lessor). The Financial Accounting Standards Board and the International Accounting Standards Board are responsible for setting the guidelines for accounting policies in the United States and in the European Union, respectively. The former has introduced the Statement No. 13 (FASB, 1976) while the latter has released the International Accounting Standard 17 (IASB, 2010) in order to prescribe accounting issues in SLB transactions. Although these boards have differences on the treatment of leases, a joint project, with the aim to develop a common standard that would ensure that all assets and liabilities arising under lease contracts are recognised in the balance sheet, was announced in 2006 (IASB, 2012). As the trend in the standard setting bodies is towards capital/finance leases, this study is focused on capital/finance SLB transactions and for this reason the criterion that the lease term is equal to or exceeds 75 percent of the economic life of the asset will be used.

At the commencement of the SLB term, leases should be capitalised in the balance sheet of the lessee as assets and liabilities at an amount equal to the fair value of the leased property or, if lower, the present value of the minimum lease payments. The interest rate implicit in the lease should be used to discount the present value of the minimum lease payments, if this is practicable to determine, otherwise the lessee's incremental borrowing rate should be used. The fair value is the amount for which an asset could be exchanged between knowledgeable, willing parties in an arm's length transaction. The interest rate implicit in the lease is the discount rate that, at the inception of the lease, causes the aggregate present value of the minimum lease payments to be equal to the sum of the fair value of the leased asset while the lessee's incremental borrowing rate of interest is the rate of interest the lessee would have to pay on a similar lease or, if that is not determinable, the rate that, at the inception of the lease, the lessee would incur to borrow over a similar term, and with a similar security, the funds necessary to purchase the asset. The difference between the fair value and the book value is recognised as unearned profit on SLB and also the leased back asset is depreciated with a policy consistent with that for depreciable assets that are owned (FASB, 1976; IASB, 2010).

A SLB transaction can take place regardless of the fair value and the present value of the minimum lease payments. However, a company prefers the fair value to be higher than the present value of the minimum lease payments in order to yield a positive net present value and appraise the SLB investment. The following inequality presents the basic condition for a value creating SLB transaction:

$$\mathrm{FV} \geq \mathrm{PVLP} \Leftrightarrow \mathrm{FV} \geq \mathrm{PMT} \times \frac{1-(1+\mathrm{LIBR})^{-\mathrm{T}}}{\mathrm{LIBR}} \Leftrightarrow$$

$$\Leftrightarrow \mathrm{FV} \geq \frac{\mathrm{FV}}{\frac{1-(1+\mathrm{IRIL})^{-\mathrm{T}}}{\mathrm{IRIL}}} \times \frac{1-(1+\mathrm{LIBR})^{-\mathrm{T}}}{\mathrm{LIBR}}$$

The fair value of an asset (FV) should be greater or equal to the present value of minimum lease payments (PVLP). PVLP is calculated as an ordinary annuity, the product of minimum lease payments (PMT) and a discounting factor with inputs the lessee's incremental borrowing rate (LIBR) and the term of the SLB agreement (T). The PMT is also calculated as an ordinary annuity, the division of FV and a discounting factor with inputs the interest rate implicit in the lease (IRIL) and T.

By subtracting FV from each side and then factoring the right side, the previous inequality can be rewritten as follows:

$$0 \geq \mathrm{FV}\left(\frac{[1-(1+\mathrm{LIBR})^{-\mathrm{T}}]/\mathrm{LIBR}}{[1-(1+\mathrm{IRIL})^{-\mathrm{T}}]/\mathrm{IRIL}} - 1\right)$$

As FV, LIBR, and IRIL are always positive numbers the previous inequality is true if the second term of the right side is negative and more specifically if the ratio of discounting factors is lower than 1. The following inequality presents the final SLB condition where (DF) stands for discounting factor:

$$1 \geq \frac{\mathrm{DF}_{\mathrm{T}}^{\mathrm{LIBR}}}{\mathrm{DF}_{\mathrm{T}}^{\mathrm{IRIL}}}$$

6.3 Mathematical formulation

6.3.1 Problem description

As in the three previous chapters, in this chapter the proposed model, which integrates SLB modelling, considers the design of a multiproduct, four-echelon SCN as shown in Figure 6-1. The problem under investigation is similar to that presented in Section 3.3.1, in Section 4.3.1, and in Section 5.3.1, where our main aim is to satisfy customers' product demand by establishing the optimal SCN in terms of NOPAT and unearned profit on SLB. However, a vital aspect that distinguishes the proposed model in this chapter from models M1, M2, and M3 is the fact that the ownership status of warehouses and distribution centres is evaluated at each time period and is not stable during the planning horizon.

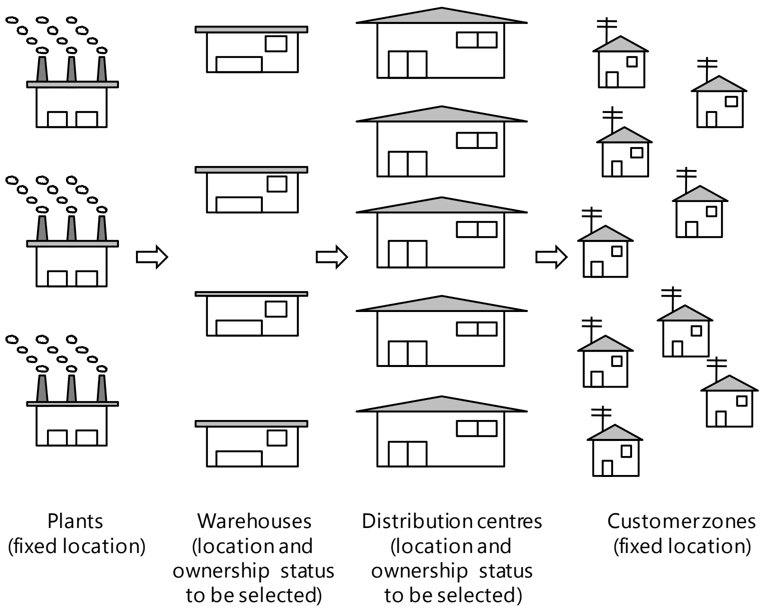


Figure 6-1: The SCN considered in this chapter

The SCN decisions to be determined by the proposed model are the same as those in model M1 along with two additional decisions regarding the SLB modelling. We repeat the same decisions here for case of reference together with the newly introduced decisions.

Strategic decisions ("here-and-now"):

I. The number, location and capacity of warehouses to be set up
II. The number, location and capacity of distribution centres to be set up
III. The transportation links that need to be established in the network

and tactical ("wait-and-see"):

IV. The number and timing of warehouses to be sold and leased back
V. The number and timing of distribution centres to be sold and leased back
VI. The flows of products in the network
VII. The production rates at plants
VIII. The inventory levels at each warehouse
IX. The inventory levels at each distribution centre

The objective is to find the optimal SCN configuration and ownership status that maximise the company's expected value of NOPAT and expected value of unearned profit on SLB (UPSLB), under all scenarios, over the planning horizon, taking into account several design, operating, and financial constraints.

6.3.2 Mathematical model (M4)

The above problem is formulated through a MINLP problem (M4). In contrast to models M1 and M2, where uncertainty concerned only product demands, and to model M3, where uncertainty concerned the economic environment, in model M4 uncertainty concerns the real estate market and product demands and is expressed though four parameters. These are product demand, FV, LIBR, and IRIL. In model M4 these four parameters are time-varying and uncertain and thus the dynamic nature is maintained. The scenario approach, as explained in detail in Section 3.2, is employed in handling transient uncertainty in real estate market and in product demand.

The planning horizon is based on the fixed asset's economic life (EL) since a SLB term (T) should be at least 75 percent of asset's EL and should be completed at the end of asset's EL. In Figure 6-2 the planning period of a fixed asset with 20 years EL is presented for better illustration purposes and in order to keep coherency with the case study application that follows on Section 6.4. The planning horizon contains the time window, five years in our case, where a SLB deal could took place. At the end of each of these time periods the SLB condition is evaluated and if it is considered value creating the SLB deal starts.

The number of scenarios is based on the EL of fixed assets and provided that each time period we have two potentially different sets of piecewise constant parameter values the total number of scenarios is $s = 1,2,\cdots,2^{\left(\frac{EL}{4}-1\right)}$. The proposed model M4 handles any one of these scenarios, as M1, M2, and M3 do, by multiplying each scenario with its probability to occur ψ_s. These probabilities satisfy the condition expressed by constraint (3.1):

$$\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s = 1 \qquad (3.1)$$

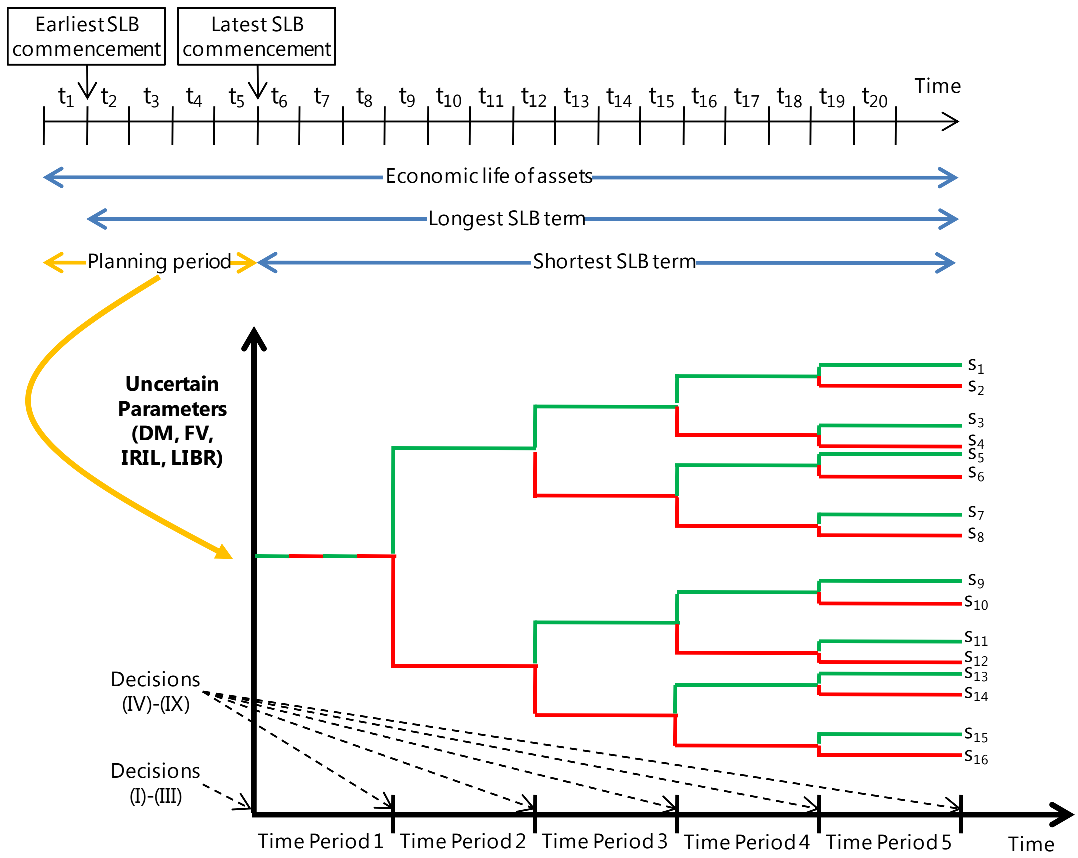


Figure 6-2: Scenarios for problems involving both "here-and-now" and "wait-and-see" decisions

6.3.3 Nomenclature

The nomenclature to be used in this chapter is consistent with that used in Chapter 5 for model M3. Here we present only those symbols that are different from those listed in Section 5.3.3 and these are either newly introduced or substituting existing ones.

Indices

s	real estate market and demand scenario (substitutes *s* which represented economic scenario)

Parameters

$AnInPaid$	annual interest paid
DR_k	depreciation rate of distribution centre *k* at each time period (substitutes DREXFA_t and DRNWFA_t)
DR_m	depreciation rate of warehouse *m* at each time period (substitutes DREXFA_t and DRNWFA_t)
EL	economic life of fixed assets
$\mathrm{FV}_{k,t}^{[s]}$	fair value of distribution centre *k* at the end of time period *t* under scenario *s*
$\mathrm{FV}_{m,t}^{[s]}$	fair value of warehouse *m* at the end of time period *t* under scenario *s*
$\mathrm{IRIL}_{k,t}^{[s]}$	interest rate implicit in the lease for distribution centre *k* at the end of time period *t* under scenario *s*
$\mathrm{IRIL}_{m,t}^{[s]}$	interest rate implicit in the lease for warehouse *m* at the end of time period *t* under scenario *s*
$\mathrm{LIBR}_{k,t}^{[s]}$	lessee's incremental borrowing rate for distribution centre *k* at the end of time period *t* under scenario *s*
$\mathrm{LIBR}_{m,t}^{[s]}$	lessee's incremental borrowing rate for warehouse *m* at the end of time period *t* under scenario *s*
TP_t	cummulative time period index (1, 2, ..., EL/4)
TR	tax rate (substitutes TR_t)

Continuous variables

PMT_k	minimum lease payments for sold and leased back distribution centre *k*
PMT_m	minimum lease payments for sold and leased back warehouse *m*
PVLP_k	present value of minimum lease payments for sold and leased back distribution centre *k*
PVLP_m	present value of minimum lease payments for sold and leased back warehouse *m*

Binary variables

$\mathrm{LPDC}_{k,t}$ 1 if distribution centre *k* is sold and leased back during time period *t*, 0 otherwise

$\mathrm{LPW}_{m,t}$ 1 if warehouse *m* is sold and leased back during time period *t*, 0 otherwise

$\mathrm{OPDC}_{k,t}$ 1 if distribution centre *k* is owned during time period *t*, 0 otherwise

$\mathrm{OPW}_{m,t}$ 1 if warehouse *m* is owned during time period *t*, 0 otherwise

6.3.4 Constraints

The basic structural and operational constraints are identical to those presented in Section 3.3.4 for model M1 and in Section 4.3.4 for model M2, and in Section 5.3.4 for model M3. However, it is logical that the financial modelling constraints are different as model M4 formulates the SLB technique, a new financial aspect that none of previous models did.

Here we will present only those constraints that are different from those presented in Section 3.3.4, in Section 4.3.4, and in Section 5.3.4. These are either newly introduced or substituting existing ones. We explain thoroughly, in cases of constraints' updating, the underlying motivation.

Non-negativity constraints

Constraints (6.1)–(6.4) are the result of newly introduced variables in model M4.

$$\mathrm{PMT}_k \geq 0, \forall k \tag{6.1}$$

$$\mathrm{PMT}_m \geq 0, \forall m \tag{6.2}$$

$$\mathrm{PVLP}_k \geq 0, \forall k \tag{6.3}$$

$$\mathrm{PVLP}_m \geq 0, \forall m \tag{6.4}$$

Financial operation constraints

The financial operation constraints in Model M4 concern the modelling of SLB technique. In specific we formulate mathematically how a SLB agreement is activated, how the minimum lease payments are calculated and activated, and how the present value of minimum lease payments is calculated and activated. The two latter figures are necessary in order to construct the objective function of our model.

Constraint (6.5) states that at each time period an established warehouse (PW_m) should be either owned ($\mathrm{OPW}_{m,t}$) by the company or sold and leased back ($\mathrm{LPW}_{m,t}$). If not established then it should be neither owned by the company nor sold and leased back. In the same manner, constraint (6.6) states that at each time period an established distribution centre (PDC_k) should be either owned ($\mathrm{OPDC}_{k,t}$) by the company or sold and leased back ($\mathrm{LPDC}_{k,t}$). If not established then it should be neither owned by the company nor sold and leased back.

$$\mathrm{PW}_m = \mathrm{OPW}_{m,t} + \mathrm{LPW}_{m,t}, \forall m, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.5}$$

$$\mathrm{PDC}_k = \mathrm{OPDC}_{k,t} + \mathrm{LPDC}_{k,t}, \forall k, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.6}$$

Constraint (6.7) ensures that when a warehouse is sold and leased back at the end of a time period then all consecutive time periods this warehouse should continue to be sold and leased back and should not be owned again. If a warehouse is owned at the end of a time period then all consecutive time periods this warehouse should either continue to be owned or sold and leased back. Similarly constraint (6.8) ensures that when a distribution centre is sold and leased back at the end of a time period then all consecutive time periods this distribution centre should continue to be sold and leased back and should not be owned again. If a distribution centre is owned at the end of a time period then all consecutive time periods this distribution centre should either continue to be owned or sold and leased back.

$$\mathrm{LPW}_{m,t-1} \leq \mathrm{LPW}_{m,t}, \forall m, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.7}$$

$$\mathrm{LPDC}_{k,t-1} \leq \mathrm{LPDC}_{k,t}, \forall k, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.8}$$

Based on the final SLB condition inequality, presented in Section 6.2.1, at each time period and under all scenarios a warehouse could be sold and leased back if the expected value of the ratio of the lessee's incremental borrowing rate discounting factor ($\mathrm{DF}_{T=EL-t}^{LIBR_{m,t}^{[s]}}$) to the discounting factor of interest rate implicit in the lease ($\mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}$) is lower than unity. However, during a planning horizon this condition could be satisfied either for consecutive time periods or for non consecutive time periods. Thus a warehouse should be either sold and leased back, at one of these time periods where the aforementioned condition is satisfied and not necessarily the first time period, or continue to be owned. The following constraint (6.9) activates the binary variable, which shows if a warehouse is sold and leased back (M is a large positive number).

$$\left(\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}\right)\left(1 - \sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{DF}_{T=EL-t}^{LIBR_{m,t}^{[s]}}}{\mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}}\right)\right) \geq \mathrm{M}\left(\mathrm{LPW}_{m,t} - 1\right), \forall m, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.9}$$

In the above constraint (6.9) two possible cases exist. The one where the binary variable at the previous time period is zero ($\mathrm{LPW}_{m,t-1} = 0$) and the other where the binary variable at the previous time period is unity ($\mathrm{LPW}_{m,t-1} = 1$). In the latter case constraint (6.7) forces the binary variable to be unity ($\mathrm{LPW}_{m,t} = 1$) and constraint (6.9) is satisfied. In the former case, constraint (6.46) is satisfied regardless of the value of the binary variable ($\mathrm{LPW}_{m,t}$), either zero or unity. However, in order to be unity the expected value of the ratio of the discounting factors must be lower or equal to unity ($\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\mathrm{DF}_{T=EL-t}^{LIBR_{m,t}^{[s]}} / \mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}} \right) \leq 1$). Thus, with this constraint the model could bypass a time period where the aforementioned condition is satisfied in order to activate the SLB deal at a next time period where more benefits could be gained.

In a similar fashion, constraint (6.10) activates the binary variable, which shows if a distribution centre is sold and leased back.

$$\left(\mathrm{LPDC}_{k,t} - \mathrm{LPDC}_{k,t-1}\right)\left(1 - \sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{DF}_{T=EL-t}^{LIBR_{k,t}^{[s]}}}{\mathrm{DF}_{T=EL-t}^{IRIL_{k,t}^{[s]}}} \right)\right) \geq \mathrm{M}\left(\mathrm{LPDC}_{k,t} - 1\right), \forall k, t = 1, \cdots, \frac{\mathrm{EL}}{4} \tag{6.10}$$

The minimum lease payments are tax deductible expenses that affect the NOPAT. The value of minimum lease payments is dynamic since it is formulated based on uncertain figures, namely, asset's fair value and interest rate implicit in the lease. However, the calculation of NOPAT must employ the formulated minimum lease payments only at the inception of the sale and lease back and use this constant value for all consecutive time periods in which the asset is sold and leased back. The following constraint (6.11) satisfies this condition for each warehouse.

$$\mathrm{PMT}_m = \sum_{t=1}^{\frac{EL}{4}} \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{FV}_{m,t}^{[s]}}{\mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}} \right) \right) \left(\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}\right) \right], \forall m \tag{6.11}$$

At the end of each time period the expected value of minimum lease payments ($\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \left(\mathrm{FV}_{m,t}^{[s]} / \mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}} \right)$) is calculated as the sum of each scenario's probability to occur (ψ_s) with the corresponding quotient of fair value ($\mathrm{FV}_{m,t}^{[s]}$) and an ordinary annuity discounting factor ($\mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}$). Then, by multiplying the expected value of minimum lease payments with the term ($\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}$) and summarizing the resulting products from all time periods we gain a constant value of minimum lease payments (PMT_m), regardless of time period.

In the case where an established warehouse is not sold and leased back the binary variable, showing whether a warehouse is sold and leased back, at all time periods is zero and thus the resulting constant value of minimum lease payments is zero since the expected value of minimum lease payments is multiplied with zero. In the case where a warehouse is sold and leased back at the end of a time period (sale leaseback commencement) the binary variable, showing whether a warehouse is sold and leased back, at that period will be unity while for all time periods previous to that will be zero and next to that will be unity. In this way the expected value of minimum lease payments is multiplied with unity only for the time period where the sale leaseback starts while for all other time periods, either before or after, is multiplied with zero. Consequently, constant value of minimum lease payments is the expected value of minimum lease payments at the commencement of the sale leaseback agreement.

In the same way constraint (6.12) shows how the aforementioned condition is satisfied for each distribution centre.

$$\mathrm{PMT}_k = \sum_{t=1}^{\frac{EL}{4}} \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{FV}_{k,t}^{[s]}}{\mathrm{DF}_{T=EL-t}^{IRIL_{k,t}^{[s]}}} \right) \right) \left(\mathrm{LPDC}_{k,t} - \mathrm{LPDC}_{k,t-1} \right) \right], \forall k \tag{6.12}$$

The assets that are sold and leased back should be presented in the left side of the balanced sheet at the inception of the lease term with a value equal to the present value of minimum lease payments and then all consecutive years they should be depreciated with rates same as those for owned assets. The present value of minimum lease payments is also dynamic since it is formulated based on uncertain figures, namely, asset's fair value, lessee's incremental borrowing rate, and interest rate implicit in the lease. However, the calculation of NOPAT must employ, for sold and leased back assets, depreciation expenses based on the formulated present value of minimum lease payments only at the inception of the sale and lease back and use this constant value for all consecutive time periods in which the asset is sold and leased back. The following constraint (6.13) satisfies this condition for each warehouse.

$$\mathrm{PVLP}_m = \sum_{t=1}^{\frac{EL}{4}} \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{FV}_{m,t}^{[s]}}{\mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}} \mathrm{DF}_{T=EL-t}^{LIBR_{m,t}^{[s]}} \right) \right) \left(\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1} \right) \right], \forall m \tag{6.13}$$

At the end of each time period the expected value of the present value of minimum lease payments ($\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\left(\mathrm{FV}_{m,t}^{[s]} / \mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}} \right) \mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{m,t}^{[s]}} \right)$) is calculated as the sum of each scenario's probability to occur (ψ_s) with the corresponding product of payments ($\mathrm{FV}_{m,t}^{[s]} / \mathrm{DF}_{T=EL-t}^{IRIL_{m,t}^{[s]}}$) and an ordinary annuity discounting factor ($\mathrm{DF}_{T=EL-t}^{LIBR_{m,t}^{[s]}}$). Then, by multiplying the expected value of the present value of minimum lease payments with the term ($\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}$) and summarizing the resulting products from all time periods we gain a constant value of present value of minimum lease payments (PVLP_m), regardless of time period. The term ($\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}$) activates the expected value of the present value of minimum lease payments, only at the inception of the sale and leaseback agreement, as in constraint (6.11).

In an analogous manner constraint (6.14) shows how the aforementioned condition is satisfied for each distribution centre.

$$\mathrm{PVLP_k} = \sum_{t=1}^{\frac{EL}{4}} \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \left(\frac{\mathrm{FV}_{k,t}^{[s]}}{\mathrm{DF}_{T=EL-t}^{\mathrm{IRIL}_{k,t}^{[s]}}} \mathrm{DF}_{T=EL-t}^{\mathrm{LIBR}_{k,t}^{[s]}} \right) \right) \left(\mathrm{LPDC}_{k,t} - \mathrm{LPDC}_{k,t-1} \right) \right], \forall k \tag{6.14}$$

6.3.5 Objective function

The objective of the optimisation model is to maximise, under all scenarios, regarding real estate market and product demand, and over the planning horizon, two financial figures that a SLB agreement affects, namely, the expected value of NOPAT and the expected value of UPSLB. The former is calculated based on the income statement of a company and is guided by the rule that revenues minus expenses yield the income. The latter is calculated based on accounting standards for capital/finance leases and more specifically as the difference between the sold and leased asset's fair market value minus its book value shown on the balance sheet of the company.

Initially, net sales are calculated as the sum of product's price and demand. Then various expenses are subtracted and the result is multiplied with the term $(1 - \mathrm{TR})$ in order to attain NOPAT under each scenario and for each time period. Then by multiplying these NOPAT's with each scenario's probability to occur and summarizing the resulting products for all time periods we gain the total expected value of NOPAT under all scenarios and for the planning horizon.

The expenses are: (a) production cost; (b) transportation cost; (c) product handling cost; (d) inventory cost; (e) depreciation for both owned and sold and leased back assets; (f) leasing cost; and (g) Annual Interest Paid ($\mathrm{AnIntPaid}$). Expenses (a) to (d), which are realised in order to transform raw materials to products and deliver them to final customers, constitute the COGS. With the exception of inventory cost, all aforementioned expenses are calculated as the sum of product's unit cost and quantity of product produced, transferred, or handled. Regarding inventory cost, the arithmetic mean of the starting and finishing inventories is multiplied with the unit inventory cost as inventories vary linearly over each time period. Depreciation is divided into this related to owned fixed assets and this related to sold and leased back assets. The former is calculated as the product of depreciation rate and establishment/historical cost of these assets, provided that the assets are owned, while the latter is calculated as the product of depreciation rate and the present value of minimum lease payments for these assets, provided that these assets are sold and leased back. Leasing cost is the minimum lease payments, provided that the assets are sold and leased back. Finally, Annual Interest Paid is the amount of interest a company pays to serve its loans.

The second constituent of the objective function is the UPSLB, the excess of the asset's fair value and book value at the commencement of the SLB agreement. In the case of a warehouse, the fair value of each warehouse at each time period and under all scenarios is calculated as the sum of each scenario's probability to occur with the corresponding fair value ($\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \mathrm{FV}_{m,t}^{[s]}$). Then, the book value of the sold and leased back warehouse is subtracted in order to gain the unearned profit on sale and leaseback of each warehouse at each time period. The book value of a warehouse at each time period is the establishment/historical cost of that warehouse minus accumulated depreciation for all the yeas until the current time period ($(1 - \mathrm{TP}_t \mathrm{DR}_m)\mathrm{C}_m^{WF}$). By multiplying the expected value of unearned profit on sale and leaseback of each warehouse at each time period with the term ($\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1}$) and summarizing the resulting products from all time periods we gain the expected value of unearned profit on sale and leaseback of each warehouse only at the inception of the sale and leaseback agreement. Finally, by summarizing these values from all sold and leased back warehouses we attain the expected value of unearned profit on sale and leaseback of all warehouses. In an analogous fashion, the expected value of unearned profit on sale and leaseback of all distribution centres is estimated.

$$
\begin{aligned}
\mathrm{OBJ}^4\colon \max \sum_{t=1}^{\frac{EL}{4}} \sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \Bigg[(1-\mathrm{TR}) \Bigg(& \underbrace{\sum_{i,l,t} \mathrm{PRICE}_{ilt}^{[s]} \mathrm{DM}_{ilt}^{[s]}}_{\substack{\textit{net sales}}} - \underbrace{\sum_{i,j} \mathrm{C}_{ij}^{P} \mathrm{P}_{ijt}^{[s]}}_{\substack{\textit{production} \\ \textit{cost}}} - \underbrace{\sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]}}_{\substack{\textit{transportation cost} \\ \textit{plants to warehouses}}} \\
& - \underbrace{\sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]}}_{\substack{\textit{transportation cost} \\ \textit{warehouses to} \\ \textit{distribution centres}}} - \underbrace{\sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]}}_{\substack{\textit{transportation cost} \\ \textit{distribution centres to} \\ \textit{customer zones}}} - \underbrace{\sum_{i,m} \mathrm{C}_{im}^{WH} \left(\sum_{j} \mathrm{Q}_{ijmt}^{[s]} \right)}_{\substack{\textit{handling cost} \\ \textit{warehouses}}} \\
& - \underbrace{\sum_{i,k} \mathrm{C}_{ik}^{DH} \left(\sum_{m} \mathrm{Q}_{imkt}^{[s]} \right)}_{\substack{\textit{handling cost} \\ \textit{distribution centres}}} - \underbrace{\sum_{i,j} \mathrm{C}_{ij}^{I} \frac{\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{ij,t-1}^{[s]}}{2}}_{\substack{\textit{inventory cost} \\ \textit{plants}}} - \underbrace{\sum_{i,m} \mathrm{C}_{im}^{I} \frac{\mathrm{I}_{imt}^{[s]} + \mathrm{I}_{im,t-1}^{[s]}}{2}}_{\substack{\textit{inventory cost} \\ \textit{warehouses}}} \\
& - \underbrace{\sum_{i,k} \mathrm{C}_{ik}^{I} \frac{\mathrm{I}_{ikt}^{[s]} + \mathrm{I}_{ik,t-1}^{[s]}}{2}}_{\substack{\textit{inventory cost} \\ \textit{distribution centres}}} - \underbrace{\sum_{m} \mathrm{DR}_m \mathrm{C}_m^{WF} \mathrm{OPW}_{m,t}}_{\substack{\textit{depreciation} \\ \textit{owned} \\ \textit{warehouses}}} - \underbrace{\sum_{m} \mathrm{DR}_m \mathrm{PVLP}_m \mathrm{LPW}_{m,t}}_{\substack{\textit{depreciation} \\ \textit{sold leased back} \\ \textit{warehouses}}} \\
& - \underbrace{\sum_{k} \mathrm{DR}_k \mathrm{C}_k^{DF} \mathrm{OPDC}_{k,t}}_{\substack{\textit{depreciation} \\ \textit{owned} \\ \textit{distribution centres}}} - \underbrace{\sum_{k} \mathrm{DR}_k \mathrm{PVLP}_k \mathrm{LPDC}_{k,t}}_{\substack{\textit{depreciation} \\ \textit{sold leased back} \\ \textit{distribution centres}}} - \underbrace{\sum_{m} \mathrm{PMT}_m \mathrm{LPW}_{m,t}}_{\substack{\textit{minimum lease payments} \\ \textit{sold leased back} \\ \textit{warehouses}}} \\
& - \underbrace{\sum_{k} \mathrm{PMT}_k \mathrm{LPDC}_{k,t}}_{\substack{\textit{minimum lease payments} \\ \textit{sold leased back} \\ \textit{distribution centres}}} - AnIntPaid \Bigg) \Bigg] \\
& + \sum_{m} \sum_{t=1}^{\frac{EL}{4}} \left\{ \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \mathrm{FV}_{m,t}^{[s]} \right) - (1 - \mathrm{TP}_t \mathrm{DR}_m) \mathrm{C}_m^{WF} \right] \left(\mathrm{LPW}_{m,t} - \mathrm{LPW}_{m,t-1} \right) \right\} \\
& + \sum_{k} \sum_{t=1}^{\frac{EL}{4}} \left\{ \left[\left(\sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \mathrm{FV}_{k,t}^{[s]} \right) - (1 - \mathrm{TP}_t \mathrm{DR}_k) \mathrm{C}_k^{DF} \right] \left(\mathrm{LPDC}_{k,t} - \mathrm{LPDC}_{k,t-1} \right) \right\}
\end{aligned}
$$

6.3.6 Solution approach

The above mathematical model including objective function OBJ^4 and constraints (3.1)–(3.11), (3.15)–(3.24), (3.28)–(3.36), (4.1), (5.1)–(5.6), and (6.1)–(6.14) is a Non-Convex MINLP that is solved by using the standard branch-and-bound techniques. The nonlinearities arise in objective function.

6.4 A case study

6.4.1 Background

The applicability of the proposed MINLP model M4 is illustrated through its implementation in the same industrial company presented in Chapter 3, in Chapter 4, and in Chapter 5. However, the size of the problem is not the same, as in Sections 3.4.1, 4.4.1, and 5.4.1 and the data are not identical because the SLB modelling requires data from the real estate market and also the total number of scenarios is 16. For this reason we will provide all data but in cases were these are identical to those data presented in previous sections they will be omitted.

There are two production plants which consume four shared manufacturing resources and produce eight products. These products should arrive at eight customer zones located in different places, in order to satisfy their demands, through a network of three potential warehouses and four potential distribution centres, all having 20 years of economic life, as shown in Figure 6-3.

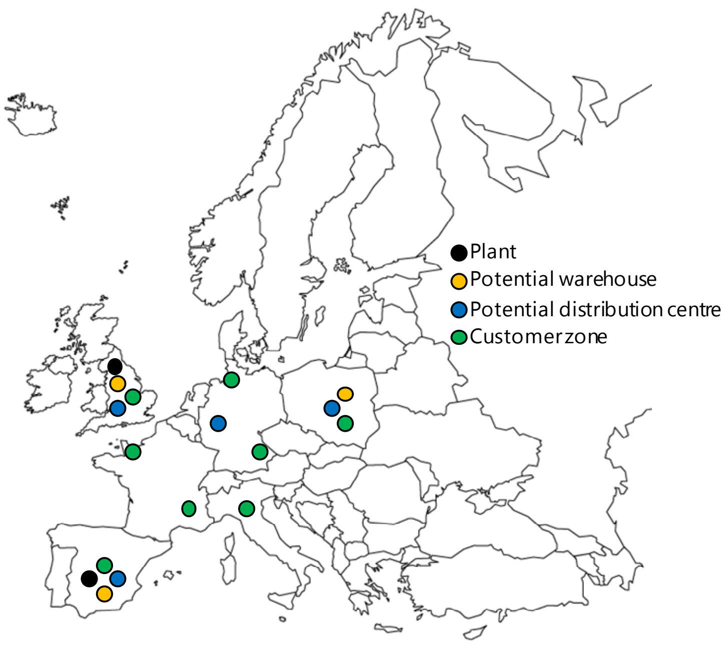


Figure 6-3: The case study SCN

For confidentiality reasons the locations of plants, warehouses, distribution centres, and customer zones are referred with numbers and for the financial data the relative money units have substitute the real currency units.

Plants

Each plant produces all products from a portfolio of eight different products using four share production resources and subjected to a maximum production capacity. The minimum production capacity is assumed to be zero. The minimum quantity of products that can practically and economically be transferred to each warehouse is equal to 100 whereas the maximum is 10,000 for each product and during each time period. Each plant generates costs because of production, storage, and transportation of products to warehouses. In each plant and for each product there are initial inventories, equal to 10 percent of the maximum production capacity of the plant. For every plant a safety stock requirement is set equal to 10 percent of the total quantity of all products transferred from this plant to all warehouses.

All data are identical to those in Section 5.4.1 and are presented in Tables 5-1 to 5-4.

Warehouses

The coefficient relating the capacity of a warehouse to the throughput of each product handled is taken to be one percent ($\gamma_{im} = 0.01$). Warehouses hold no initial inventory and the safety stock requirement is set equal to five percent of the total quantity of all products transferred from this warehouse to all distribution centres. The minimum quantity of products that can practically and economically be transferred to each customer zone is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

All data regarding costs and capacities are identical to those in Section 5.4.1 and are presented in Tables 5-5 to 5-7.

Distribution centres

The coefficient relating the capacity of a distribution centre to the throughput of each product handled is taken to be one percent ($\gamma_{ik} = 0.01$). Distribution centres hold no initial inventory and the safety stock requirement is set equal to one percent of the total quantity of all products transferred from this distribution centre to all customer zones. The minimum quantity of products that can practically and economically be transferred to each customer zone is equal to 100 whereas the maximum is 10,000 for each product and during each time period.

All data regarding costs and capacities are identical to those in Section 5.4.1 and are presented in Tables 5-8 to 5-10.

Customer zones

For the fist time period product demands for the eight customer zones are given in Table 6-1. In the next time period real estate market and product demand uncertainty is becoming more discernible so two predictions are made, as shown in Tables 6-2 to 6-3. In a similar manner, in the third time period two predictions are made for each one of the previous' period predictions (see Tables 6-4 to 6-7). In the fourth time period, again two predictions are made for each one of the previous' period predictions (see Tables 6-8 to 6-15). Overall, we consider 16 distinct scenarios organised in an analogous tree structure of the type shown in Figure 6-2.

The price of each product in each customer zone is identical to those in Section 5.4.1 and is presented in Table 5-24.

Table 6-1: Demand for product *i* from customer zone *l* over the first period (all scenarios)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	440	500	610	480	370	550	560	290
i_2	550	600	570	320	230	360	210	310
i_3	620	390	530	310	230	390	290	300
i_4	430	360	720	220	290	250	370	600
i_5	520	440	380	190	460	180	320	540
i_6	370	530	250	580	540	330	190	580
i_7	450	470	480	310	410	450	170	450
i_8	440	310	490	660	270	460	160	450

Note: i/y means items per year.

Table 6-2: Demand for product *i* from customer zone *l* over the second period (scenario 1-8)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	484	550	671	528	407	605	616	319
i_2	605	660	627	352	253	396	231	341
i_3	682	429	583	341	253	429	319	330
i_4	473	396	792	242	319	275	407	660
i_5	572	484	418	209	506	198	352	594
i_6	407	583	275	638	594	363	209	638
i_7	495	517	528	341	451	495	187	495
i_8	484	341	539	726	297	506	176	495

Note: i/y means items per year.

Table 6-3: Demand for product *i* from customer zone *l* over the second period (scenario 9-16)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	396	450	549	432	333	495	504	261
i_2	495	540	513	288	207	324	189	279
i_3	558	351	477	279	207	351	261	270
i_4	387	324	648	198	261	225	333	540
i_5	468	396	342	171	414	162	288	486
i_6	333	477	225	522	486	297	171	522
i_7	405	423	432	279	369	405	153	405
i_8	396	279	441	594	243	414	144	405

Note: i/y means items per year.

Table 6-4: Demand for product *i* from customer zone *l* over the third period (scenario 1-4)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	506	575	702	552	426	633	644	334
i_2	633	690	656	368	265	414	242	357
i_3	713	449	610	357	265	449	334	345
i_4	495	414	828	253	334	288	426	690
i_5	598	506	437	219	529	207	368	621
i_6	426	610	288	667	621	380	219	667
i_7	518	541	552	357	472	518	196	518
i_8	506	357	564	759	311	529	184	518

Note: i/y means items per year.

Table 6-5: Demand for product *i* from customer zone *l* over the third period (scenario 5-8)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	463	526	641	505	389	578	589	305
i_2	578	631	599	337	242	379	221	326
i_3	652	410	557	326	242	410	305	316
i_4	452	379	757	232	305	263	389	631
i_5	547	463	400	200	484	190	337	568
i_6	389	557	263	610	568	347	200	610
i_7	473	494	505	326	431	473	179	473
i_8	463	326	515	694	284	484	169	473

Note: i/y means items per year.

Table 6-6: Demand for product *i* from customer zone *l* over the third period (scenario 9-12)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	414	471	574	452	348	518	527	273
i_2	518	565	537	301	217	339	198	292
i_3	584	367	499	292	217	367	273	283
i_4	405	339	678	207	273	236	348	565
i_5	490	414	358	179	433	170	301	508
i_6	348	499	236	546	508	311	179	546
i_7	424	443	452	292	386	424	160	424
i_8	414	292	461	621	254	433	151	424

Note: i/y means items per year.

Table 6-7: Demand for product *i* from customer zone *l* over the third period (scenario 13-16)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	379	430	525	413	319	473	482	250
i_2	473	516	490	276	198	310	181	267
i_3	533	336	456	267	198	336	250	258
i_4	370	310	619	190	250	215	319	516
i_5	447	379	327	164	396	155	276	465
i_6	319	456	215	499	465	284	164	499
i_7	387	404	413	267	353	387	147	387
i_8	379	267	422	568	233	396	138	387

Note: i/y means items per year.

Table 6-8: Demand for product *i* from customer zone *l* over the fourth period (scenario 1-2)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	519	590	720	566	437	649	661	343
i_2	649	708	673	378	272	425	249	366
i_3	731	461	626	366	272	461	343	354
i_4	508	425	849	260	343	296	437	708
i_5	613	519	448	225	543	213	378	637
i_6	437	626	296	684	637	390	225	684
i_7	531	555	566	366	484	531	201	531
i_8	519	366	579	778	319	543	189	531

Note: i/y means items per year.

Table 6-9: Demand for product *i* from customer zone *l* over the fourth period (scenario 3-4)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	494	561	685	539	416	618	628	326
i_2	618	673	640	359	259	404	236	349
i_3	696	438	595	349	259	438	326	337
i_4	483	404	808	247	326	281	416	673
i_5	584	494	427	214	516	202	359	606
i_6	416	595	281	651	606	371	214	651
i_7	506	528	539	349	461	506	192	506
i_8	494	349	550	741	304	516	180	506

Note: i/y means items per year.

Table 6-10: Demand for product *i* from customer zone *l* over the fourth period (scenario 5-6)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	475	540	658	518	399	593	604	313
i_2	593	647	614	346	249	389	227	335
i_3	669	421	571	335	249	421	313	324
i_4	464	389	776	238	313	270	399	647
i_5	561	475	410	205	497	195	346	583
i_6	399	571	270	626	583	356	205	626
i_7	485	507	518	335	442	485	184	485
i_8	475	335	528	712	292	497	174	485

Note: i/y means items per year.

Table 6-11: Demand for product *i* from customer zone *l* over the fourth period (scenario 7-8)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	452	513	625	493	380	564	575	298
i_2	564	616	585	329	236	370	216	318
i_3	636	400	544	318	236	400	298	309
i_4	441	370	739	227	298	257	380	616
i_5	534	452	390	195	472	186	329	554
i_6	380	544	257	595	554	339	195	595
i_7	462	482	493	318	421	462	175	462
i_8	452	318	503	677	277	472	165	462

Note: i/y means items per year.

Table 6-12: Demand for product *i* from customer zone *l* over the fourth period (scenario 9-10)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	425	483	589	464	357	531	541	280
i_2	531	580	551	309	223	348	203	300
i_3	599	377	512	300	223	377	280	291
i_4	416	348	695	213	280	242	357	580
i_5	503	425	367	184	444	175	309	521
i_6	357	512	242	560	521	319	184	560
i_7	435	455	464	300	396	435	164	435
i_8	425	300	473	637	261	444	155	435

Note: i/y means items per year.

Table 6-13: Demand for product *i* from customer zone *l* over the fourth period (scenario 11-12)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	404	460	560	441	340	506	514	267
i_2	506	551	524	294	212	331	194	285
i_3	570	358	487	285	212	358	267	276
i_4	395	331	662	202	267	231	340	551
i_5	478	404	350	175	423	166	294	496
i_6	340	487	231	533	496	304	175	533
i_7	414	432	441	285	377	414	156	414
i_8	404	285	450	606	248	423	148	414

Note: i/y means items per year.

Table 6-14: Demand for product *i* from customer zone *l* over the fourth period (scenario 13-14)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	389	441	539	424	327	485	495	257
i_2	485	529	503	283	203	318	186	274
i_3	547	345	468	274	203	345	257	265
i_4	380	318	635	195	257	221	327	529
i_5	459	389	336	169	406	159	283	477
i_6	327	468	221	512	477	292	169	512
i_7	397	415	424	274	362	397	151	397
i_8	389	274	433	583	239	406	142	397

Note: i/y means items per year.

Table 6-15: Demand for product *i* from customer zone *l* over the fourth period (scenario 15-16)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	370	420	512	403	312	462	470	244
i_2	462	504	478	270	194	303	177	261
i_3	520	328	445	261	194	328	244	252
i_4	361	303	604	186	244	210	312	504
i_5	436	370	319	160	387	152	270	454
i_6	312	445	210	487	454	277	160	487
i_7	378	394	403	261	345	378	144	378
i_8	370	261	412	554	228	387	135	378

Note: i/y means items per year.

Table 6-16: Demand for product *i* from customer zone *l* over the fifth period (scenario 1)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	525	596	728	572	442	656	668	347
i_2	656	716	680	382	275	430	252	370
i_3	739	466	633	370	275	466	347	358
i_4	514	430	858	263	347	299	442	716
i_5	620	525	453	228	549	216	382	644
i_6	442	633	299	691	644	394	228	691
i_7	537	561	572	370	489	537	204	537
i_8	525	370	585	786	323	549	191	537

Note: i/y means items per year.

Table 6-17: Demand for product *i* from customer zone *l* over the fifth period (scenario 2)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	514	585	713	561	433	643	655	340
i_2	643	701	667	375	270	421	247	363
i_3	724	457	620	363	270	457	340	351
i_4	503	421	841	258	340	294	433	701
i_5	607	514	444	223	538	211	375	631
i_6	433	620	294	678	631	387	223	678
i_7	526	550	561	363	480	526	199	526
i_8	514	363	574	771	316	538	188	526

Note: i/y means items per year.

Table 6-18: Demand for product *i* from customer zone *l* over the fifth period (scenario 3)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	499	567	692	545	421	625	635	330
i_2	625	680	647	363	262	409	239	353
i_3	703	443	601	353	262	443	330	341
i_4	488	409	817	250	330	284	421	680
i_5	590	499	432	217	522	205	363	613
i_6	421	601	284	658	613	375	217	658
i_7	512	534	545	353	466	512	194	512
i_8	499	353	556	749	308	522	182	512

Note: i/y means items per year.

Table 6-19: Demand for product *i* from customer zone *l* over the fifth period (scenario 4)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	490	556	679	534	412	612	622	323
i_2	612	667	634	356	257	400	234	346
i_3	690	434	590	346	257	434	323	334
i_4	479	400	800	245	323	279	412	667
i_5	579	490	423	212	511	200	356	600
i_6	412	590	279	645	600	368	212	645
i_7	501	523	534	346	457	501	191	501
i_8	490	346	545	734	301	511	179	501

Note: i/y means items per year.

Table 6-20: Demand for product *i* from customer zone *l* over the fifth period (scenario 5)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	480	546	665	524	403	599	611	317
i_2	599	654	621	350	252	393	230	339
i_3	676	426	577	339	252	426	317	328
i_4	469	393	784	241	317	273	403	654
i_5	567	480	415	208	502	197	350	589
i_6	403	577	273	633	589	360	208	633
i_7	490	513	524	339	447	490	186	490
i_8	480	339	534	720	295	502	176	490

Note: i/y means items per year.

Table 6-21: Demand for product *i* from customer zone *l* over the fifth period (scenario 6)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	471	535	652	513	396	588	598	310
i_2	588	641	608	343	247	386	225	332
i_3	663	417	566	332	247	417	310	321
i_4	460	386	769	236	310	268	396	641
i_5	556	471	406	203	493	194	343	578
i_6	396	566	268	620	578	353	203	620
i_7	481	502	513	332	438	481	183	481
i_8	471	332	523	705	290	493	173	481

Note: i/y means items per year.

Table 6-22: Demand for product *i* from customer zone *l* over the fifth period (scenario 7)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	457	519	632	498	384	570	581	301
i_2	570	623	591	333	239	374	219	322
i_3	643	404	550	322	239	404	301	313
i_4	446	374	747	230	301	260	384	623
i_5	540	457	394	197	477	188	333	560
i_6	384	550	260	601	560	343	197	601
i_7	467	487	498	322	426	467	177	467
i_8	457	322	509	684	280	477	167	467

Note: i/y means items per year.

Table 6-23: Demand for product *i* from customer zone *l* over the fifth period (scenario 8)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	448	508	619	489	377	559	570	296
i_2	559	610	580	326	234	367	214	315
i_3	630	396	539	315	234	396	296	306
i_4	437	367	732	225	296	255	377	610
i_5	529	448	387	194	468	185	326	549
i_6	377	539	255	590	549	336	194	590
i_7	458	478	489	315	417	458	174	458
i_8	448	315	498	671	275	468	164	458

Note: i/y means items per year.

Table 6-24: Demand for product *i* from customer zone *l* over the fifth period (scenario 9)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	430	488	595	469	361	537	547	283
i_2	537	586	557	313	226	352	206	303
i_3	605	381	518	303	226	381	283	294
i_4	421	352	702	216	283	245	361	586
i_5	509	430	371	186	449	177	313	527
i_6	361	518	245	566	527	323	186	566
i_7	440	460	469	303	400	440	166	440
i_8	430	303	478	644	264	449	157	440

Note: i/y means items per year.

Table 6-25: Demand for product *i* from customer zone *l* over the fifth period (scenario 10)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	421	479	584	460	354	526	536	278
i_2	526	575	546	306	221	345	201	297
i_3	594	374	507	297	221	374	278	289
i_4	412	345	689	211	278	240	354	575
i_5	498	421	364	183	440	174	306	516
i_6	354	507	240	555	516	316	183	555
i_7	431	451	460	297	393	431	163	431
i_8	421	297	469	631	259	440	154	431

Note: i/y means items per year.

Table 6-26: Demand for product *i* from customer zone *l* over the fifth period (scenario 11)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	409	465	566	446	344	512	520	270
i_2	512	557	530	297	215	335	196	288
i_3	576	362	492	288	215	362	270	279
i_4	399	335	669	205	270	234	344	557
i_5	483	409	354	177	428	168	297	501
i_6	344	492	234	539	501	308	177	539
i_7	419	437	446	288	381	419	158	419
i_8	409	288	455	613	251	428	150	419

Note: i/y means items per year.

Table 6-27: Demand for product *i* from customer zone *l* over the fifth period (scenario 12)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	400	456	555	437	337	501	509	265
i_2	501	546	519	292	210	328	193	283
i_3	565	355	483	283	210	355	265	274
i_4	392	328	656	200	265	229	337	546
i_5	474	400	347	174	419	165	292	492
i_6	337	483	229	528	492	301	174	528
i_7	410	428	437	283	374	410	155	410
i_8	400	283	446	600	246	419	147	410

Note: i/y means items per year.

Table 6-28: Demand for product *i* from customer zone *l* over the fifth period (scenario 13)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	393	446	545	429	331	490	500	260
i_2	490	535	509	286	206	322	188	277
i_3	553	349	473	277	206	349	260	268
i_4	384	322	642	197	260	224	331	535
i_5	464	393	340	171	411	161	286	482
i_6	331	473	224	518	482	295	171	518
i_7	401	420	429	277	366	401	153	401
i_8	393	277	438	589	242	411	144	401

Note: i/y means items per year.

Table 6-29: Demand for product *i* from customer zone *l* over the fifth period (scenario 14)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	386	437	534	420	324	481	491	255
i_2	481	524	498	281	201	315	185	272
i_3	542	342	464	272	201	342	255	263
i_4	377	315	629	194	255	219	324	524
i_5	455	386	333	168	402	158	281	473
i_6	324	464	219	507	473	290	168	507
i_7	394	411	420	272	359	394	150	394
i_8	386	272	429	578	237	402	141	394

Note: i/y means items per year.

Table 6-30: Demand for product *i* from customer zone *l* over the fifth period (scenario 15)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	374	425	518	408	316	467	475	247
i_2	467	510	483	273	196	307	179	264
i_3	526	332	450	264	196	332	247	255
i_4	365	307	611	188	247	213	316	510
i_5	441	374	323	162	391	154	273	459
i_6	316	450	213	492	459	280	162	492
i_7	382	398	408	264	349	382	146	382
i_8	374	264	417	560	231	391	137	382

Note: i/y means items per year.

Table 6-31: Demand for product *i* from customer zone *l* over the fifth period (scenario 16)

Product	Customer zone (i/y)							
	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
i_1	367	416	507	399	309	458	466	242
i_2	458	499	474	268	193	300	176	259
i_3	515	325	441	259	193	325	242	250
i_4	358	300	598	185	242	208	309	499
i_5	432	367	316	159	384	151	268	450
i_6	309	441	208	483	450	275	159	483
i_7	375	391	399	259	342	375	143	375
i_8	367	259	408	549	226	384	134	375

Note: i/y means items per year.

Financial operation

The company depreciates its assets with the straight line method and is for both warehouses and distribution centres 5.00% per year. Moreover, the tax rate is 30.00% per year and the annual interest paid is estimated at 50,000 RMU per year.

The three uncertain parameters that express into a large extend the real estate market are presented in Tables 6-32 to 6-37. Product demand, which is the fourth uncertain parameter in model M4, has been presented in Section 6.4.1. These parameters have been estimated by company's managers and are in accordance with the scenario tree structure presented in Figure 6-2. The probabilities of all scenarios are equal ($\psi_1 = \psi_2 = \cdots = \psi_{16} = 0.0625$).

Table 6-32: Fair value of warehouses under each scenario *s*

Fair value ($FV_{mt}^{[s]}$)	Scenario (RMU)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$m_1 \cdot t_1$	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000	45000
$m_1 \cdot t_2$	54000	54000	54000	54000	54000	54000	54000	54000	40500	40500	40500	40500	40500	40500	40500	40500
$m_1 \cdot t_3$	56700	56700	56700	56700	45900	45900	45900	45900	46575	46575	46575	46575	38475	38475	38475	38475
$m_1 \cdot t_4$	62370	62370	53865	53865	48195	48195	41310	41310	51233	51233	41918	41918	42323	42323	34628	34628
$m_1 \cdot t_5$	65489	59252	56558	48479	50605	43376	59400	37179	57637	50720	47157	40891	47613	41264	36359	33779
$m_2 \cdot t_1$	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500	42500
$m_2 \cdot t_2$	48875	48875	48875	48875	48875	48875	48875	48875	38250	38250	38250	38250	38250	38250	38250	38250
$m_2 \cdot t_3$	51319	51319	51319	51319	41544	41544	41544	41544	43988	43988	43988	43988	36338	36338	36338	36338
$m_2 \cdot t_4$	56451	56451	48753	48753	43621	43621	37389	37389	48386	48386	39589	39589	39971	39971	32704	32704
$m_2 \cdot t_5$	70563	55039	58503	47778	54526	42312	46737	35520	60483	47902	49486	38619	45967	38972	37609	32671
$m_3 \cdot t_1$	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500	36500
$m_3 \cdot t_2$	43800	43800	43800	43800	43800	43800	43800	43800	32850	32850	32850	32850	32850	32850	32850	32850
$m_3 \cdot t_3$	45990	45990	45990	45990	37230	37230	37230	37230	37778	37778	37778	37778	31208	31208	31208	31208
$m_3 \cdot t_4$	50589	50589	43691	43691	39092	39092	33507	33507	41555	41555	34000	34000	34328	34328	28087	28087
$m_3 \cdot t_5$	53118	48060	45875	39321	41046	35182	48180	30156	46750	41140	38250	33167	38619	33470	29491	27399

Table 6-33: Fair value of distribution centres under each scenario *s*

Fair value ($FV_{kt}^{[s]}$)	Scenario (RMU)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$k_1 \cdot t_1$	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500	38500
$k_1 \cdot t_2$	51975	51975	51975	51975	51975	51975	51975	51975	28875	28875	28875	28875	28875	28875	28875	28875
$k_1 \cdot t_3$	54574	54574	54574	54574	44179	44179	44179	44179	33206	33206	33206	33206	27431	27431	27431	27431
$k_1 \cdot t_4$	60031	60031	51845	51845	46388	46388	39761	39761	36527	36527	29886	29886	30174	30174	24688	24688
$k_1 \cdot t_5$	63033	57030	54437	46661	48707	41749	57173	35785	41093	36162	33621	29153	33946	29420	25923	24083
$k_2 \cdot t_1$	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000	43000
$k_2 \cdot t_2$	51600	51600	51600	51600	51600	51600	51600	51600	38700	38700	38700	38700	38700	38700	38700	38700
$k_2 \cdot t_3$	54180	54180	54180	54180	43860	43860	43860	43860	44505	44505	44505	44505	36765	36765	36765	36765
$k_2 \cdot t_4$	59598	59598	51471	51471	46053	46053	39474	39474	48956	48956	40055	40055	40442	40442	33089	33089
$k_2 \cdot t_5$	62578	56618	54045	46324	48356	41448	56760	35527	55075	48466	45061	39073	45497	39430	34743	32278
$k_3 \cdot t_1$	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000	41000
$k_3 \cdot t_2$	53300	53300	53300	53300	53300	53300	53300	53300	40590	40590	40590	40590	40590	40590	40590	40590
$k_3 \cdot t_3$	55965	55965	55965	55965	45305	45305	45305	45305	46679	46679	46679	46679	38561	38561	38561	38561
$k_3 \cdot t_4$	61562	61562	53167	53167	47570	47570	40775	40775	51346	51346	42011	42011	42417	42417	34704	34704
$k_3 \cdot t_5$	64640	58483	55825	47850	49949	42813	58630	36697	57765	50833	47262	40981	47719	41356	36440	33854
$k_4 \cdot t_1$	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000
$k_4 \cdot t_2$	42000	42000	42000	42000	42000	42000	42000	42000	31500	31500	31500	31500	31500	31500	31500	31500
$k_4 \cdot t_3$	44100	44100	44100	44100	35700	35700	35700	35700	36225	36225	36225	36225	29925	29925	29925	29925
$k_4 \cdot t_4$	48510	48510	41895	41895	37485	37485	32130	32130	39848	39848	32603	32603	32918	32918	26933	26933
$k_4 \cdot t_5$	50936	46085	43990	37706	39359	33737	46200	28917	44828	39449	36678	31804	37032	32095	28279	26273

Table 6-34: Lessee's incremental borrowing rate for warehouses under each scenario *s*

($\mathrm{LIBR}^{[s]}_{mt}$)	Scenario (%)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$m_1 \cdot t_1$	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
$m_1 \cdot t_2$	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20
$m_1 \cdot t_3$	4.08	4.08	4.08	4.08	5.04	5.04	5.04	5.04	6.84	6.84	6.84	6.84	8.28	8.28	8.28	8.28
$m_1 \cdot t_4$	3.67	3.67	4.50	4.50	4.54	4.54	5.54	5.54	6.16	6.16	7.50	7.50	7.45	7.45	9.11	9.11
$m_1 \cdot t_5$	3.49	3.90	4.10	4.70	4.10	4.80	5.30	5.82	6.01	6.93	7.31	8.44	7.26	8.38	8.88	9.57
$m_2 \cdot t_1$	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50
$m_2 \cdot t_2$	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
$m_2 \cdot t_3$	4.42	4.42	4.42	4.42	5.46	5.46	5.46	5.46	7.41	7.41	7.41	7.41	8.97	8.97	8.97	8.97
$m_2 \cdot t_4$	3.98	3.98	4.90	4.90	4.91	4.91	6.01	6.01	6.67	6.67	8.20	8.20	8.07	8.07	9.87	9.87
$m_2 \cdot t_5$	3.94	5.00	4.90	6.10	4.90	6.10	5.90	7.51	6.60	8.34	8.12	10.25	7.99	10.09	9.77	12.34
$m_3 \cdot t_1$	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
$m_3 \cdot t_2$	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60
$m_3 \cdot t_3$	3.74	3.74	3.74	3.74	4.62	4.62	4.62	4.62	6.27	6.27	6.27	6.27	7.59	7.59	7.59	7.59
$m_3 \cdot t_4$	3.37	3.37	4.10	4.10	4.16	4.16	5.08	5.08	5.64	5.64	6.90	6.90	6.83	6.83	8.35	8.35
$m_3 \cdot t_5$	3.20	3.50	3.70	4.30	3.70	4.40	4.80	5.33	5.50	6.35	6.73	7.76	6.66	7.68	8.14	8.77

Table 6-35: Lessee's incremental borrowing rate for distribution centres under each scenario *s*

($\mathrm{LIBR}^{[s]}_{kt}$)	Scenario (%)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$k_1 \cdot t_1$	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
$k_1 \cdot t_2$	5.60	5.60	5.60	5.60	5.60	5.60	5.60	5.60	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40
$k_1 \cdot t_3$	4.76	4.76	4.76	4.76	5.88	5.88	5.88	5.88	7.98	7.98	7.98	7.98	9.66	9.66	9.66	9.66
$k_1 \cdot t_4$	4.28	4.28	5.20	5.20	5.29	5.29	6.47	6.47	7.18	7.18	8.80	8.80	8.69	8.69	10.63	10.63
$k_1 \cdot t_5$	4.07	4.50	4.70	5.50	4.80	5.60	6.20	6.79	7.00	8.08	8.58	9.90	8.47	9.78	10.36	11.16
$k_2 \cdot t_1$	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
$k_2 \cdot t_2$	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	6.08	6.08	6.08	6.08	6.08	6.08	6.08	6.08
$k_2 \cdot t_3$	3.06	3.06	3.06	3.06	3.78	3.78	3.78	3.78	5.78	5.78	5.78	5.78	6.99	6.99	6.99	6.99
$k_2 \cdot t_4$	2.75	2.75	3.40	3.40	3.40	3.40	4.16	4.16	5.32	5.32	6.40	6.40	6.64	6.64	7.69	7.69
$k_2 \cdot t_5$	2.61	2.90	3.10	3.60	3.10	3.60	4.00	4.37	5.19	5.99	6.24	7.20	6.47	7.47	7.50	8.07
$k_3 \cdot t_1$	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
$k_3 \cdot t_2$	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
$k_3 \cdot t_3$	4.25	4.25	4.25	4.25	5.25	5.25	5.25	5.25	7.13	7.13	7.13	7.13	8.63	8.63	8.63	8.63
$k_3 \cdot t_4$	3.83	3.83	4.70	4.70	4.73	4.73	5.78	5.78	6.42	6.42	7.80	7.80	7.77	7.77	9.49	9.49
$k_3 \cdot t_5$	3.64	4.00	4.20	4.90	4.30	5.00	5.50	6.07	6.26	7.22	7.61	8.78	7.58	8.74	9.25	9.96
$k_4 \cdot t_1$	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
$k_4 \cdot t_2$	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30
$k_4 \cdot t_3$	3.57	3.57	3.57	3.57	4.41	4.41	4.41	4.41	5.99	5.99	5.99	5.99	7.25	7.25	7.25	7.25
$k_4 \cdot t_4$	3.21	3.21	3.90	3.90	3.97	3.97	4.85	4.85	5.39	5.39	6.60	6.60	6.53	6.53	7.98	7.98
$k_4 \cdot t_5$	3.05	3.40	3.50	4.10	3.60	4.20	4.60	5.09	5.26	6.06	6.44	7.43	6.37	7.35	7.78	8.38

Table 6-36: Interest rate implicit in the lease for warehouses under each scenario *s*

$(\mathrm{IRIL}_{mt}^{[s]})$	Scenario (%)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$m_1 \cdot t_1$	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
$m_1 \cdot t_2$	5.31	5.31	5.31	5.31	5.31	5.31	5.31	5.31	7.81	7.81	7.81	7.81	7.81	7.81	7.81	7.81
$m_1 \cdot t_3$	3.98	3.98	3.98	3.98	5.58	5.58	5.58	5.58	7.42	7.42	7.42	7.42	8.20	8.20	8.20	8.20
$m_1 \cdot t_4$	3.58	3.58	4.40	4.40	5.02	5.02	6.14	6.14	6.68	6.68	8.20	8.20	7.38	7.38	9.02	9.02
$m_1 \cdot t_5$	3.40	3.80	4.00	4.60	4.50	5.30	5.80	6.45	6.51	7.52	8.00	9.23	7.20	8.30	8.79	9.47
$m_2 \cdot t_1$	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
$m_2 \cdot t_2$	5.10	5.10	5.10	5.10	5.10	5.10	5.10	5.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10
$m_2 \cdot t_3$	3.83	3.83	3.83	3.83	5.36	5.36	5.36	5.36	7.70	7.70	7.70	7.70	8.51	8.51	8.51	8.51
$m_2 \cdot t_4$	3.45	3.45	4.20	4.20	4.82	4.82	5.90	5.90	6.93	6.93	8.90	8.90	7.66	7.66	9.36	9.36
$m_2 \cdot t_5$	2.93	3.60	3.60	4.40	3.90	5.10	4.10	6.20	5.54	7.28	7.57	9.35	6.51	8.04	7.96	9.83
$m_3 \cdot t_1$	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
$m_3 \cdot t_2$	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	7.43	7.43	7.43	7.43	7.43	7.43	7.43	7.43
$m_3 \cdot t_3$	3.75	3.75	3.75	3.75	4.81	4.81	4.81	4.81	5.57	5.57	5.57	5.57	8.54	8.54	8.54	8.54
$m_3 \cdot t_4$	3.38	3.38	4.10	4.10	4.33	4.33	5.29	5.29	5.01	5.01	6.10	6.10	6.41	6.41	9.39	9.39
$m_3 \cdot t_5$	3.21	3.50	3.70	4.30	3.90	4.50	4.20	5.55	4.88	5.64	5.95	6.86	6.25	7.21	9.16	9.86

Table 6-37: Interest rate implicit in the lease for distribution centres under each scenario *s*

$(\mathrm{IRIL}_{kt}^{[s]})$	Scenario (%)															
	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}
$k_1 \cdot t_1$	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75
$k_1 \cdot t_2$	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	8.34	8.34	8.34	8.34	8.34	8.34	8.34	8.34
$k_1 \cdot t_3$	4.65	4.65	4.65	4.65	7.58	7.58	7.58	7.58	7.92	7.92	7.92	7.92	10.43	10.43	10.43	10.43
$k_1 \cdot t_4$	4.32	4.32	5.10	5.10	6.82	6.82	7.96	7.96	7.13	7.13	8.70	8.70	9.39	9.39	10.95	10.95
$k_1 \cdot t_5$	3.89	4.40	4.60	5.40	6.10	7.20	5.40	8.36	6.42	8.02	8.48	9.79	9.16	10.56	10.68	11.50
$k_2 \cdot t_1$	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75
$k_2 \cdot t_2$	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04	6.41	6.41	6.41	6.41	6.41	6.41	6.41	6.41
$k_2 \cdot t_3$	3.03	3.03	3.03	3.03	4.24	4.24	4.24	4.24	6.09	6.09	6.09	6.09	6.73	6.73	6.73	6.73
$k_2 \cdot t_4$	2.73	2.73	3.30	3.30	3.82	3.82	4.66	4.66	5.48	5.48	7.00	7.00	6.06	6.06	7.40	7.40
$k_2 \cdot t_5$	2.66	3.40	3.20	3.50	3.60	4.00	4.40	4.89	5.34	6.17	6.83	7.88	5.91	6.82	7.22	7.77
$k_3 \cdot t_1$	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50
$k_3 \cdot t_2$	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55	8.78	8.78	8.78	8.78	8.78	8.78	8.78	8.78
$k_3 \cdot t_3$	4.44	4.44	4.44	4.44	5.69	5.69	5.69	5.69	6.59	6.59	6.59	6.59	10.10	10.10	10.10	10.10
$k_3 \cdot t_4$	4.00	4.00	4.90	4.90	5.12	5.12	6.26	6.26	5.93	5.93	7.20	7.20	7.58	7.58	11.11	11.11
$k_3 \cdot t_5$	3.80	4.20	4.40	5.10	4.60	5.40	5.00	6.57	5.78	6.67	7.02	8.10	7.39	8.53	10.83	11.67
$k_4 \cdot t_1$	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
$k_4 \cdot t_2$	4.39	4.39	4.39	4.39	4.39	4.39	4.39	4.39	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82
$k_4 \cdot t_3$	3.29	3.29	3.29	3.29	4.61	4.61	4.61	4.61	6.65	6.65	6.65	6.65	6.89	6.89	6.89	6.89
$k_4 \cdot t_4$	2.96	2.96	3.60	3.60	4.24	4.24	4.66	4.66	6.32	6.32	7.00	7.00	6.82	6.82	7.58	7.58
$k_4 \cdot t_5$	2.89	3.70	3.50	3.80	4.10	4.50	4.20	4.71	6.16	7.11	6.83	7.88	6.65	7.67	7.39	7.96

6.4.2 Implementation

The model M4 was solved with the DICOPT solver (NLP: CONOPT and MIP: CPLEX 11.2.0) incorporated in GAMS 22.9 software (Rosenthal, 2008). The model consisted of 56,800 constrains, 39,183 continuous variables, and 121 discrete variables. Runs were performed on a Pentium R Dual Core with 2.50GHz CPU and 3GB RAM. The solution were obtained at 5180 CPU seconds with 0% integrality gap.

Results

The optimal network structure is shown in Figure 6-4 where nodes with same numbers represent same geographical areas, product flows are under all scenarios and for the whole planning horizon, and red and green square means owned asset and sold and leased back asset, respectively. The optimal configuration is consisted of two warehouses and two distribution centres. The second warehouse is sold and leased back, at the end of the fifth time period, while all previous time periods is owned. In contrast, the first warehouse and both distribution centres are owned all time periods.

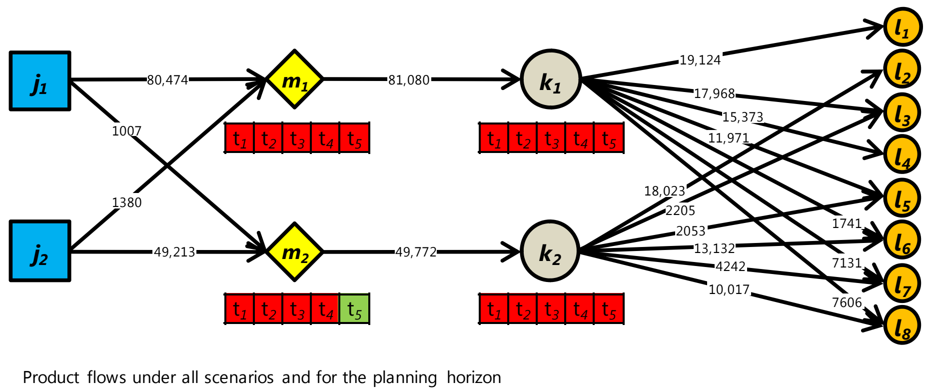


Figure 6-4: Optimal configuration from model M4 (NOPAT: 443,529 & UPSLB: 19,918)

The total expected NOPAT is 443,529 RMU and the total expected UPSLB is 19,918 RMU raised from the SLB deal closed for the second warehouse. Both plants supply products to both warehouses which, in turns, supply products only to corresponding distribution centres. The first distribution centre supplies seven customer zones whereas the second distribution centre supplies six customer zones. This optimal configuration, where selected warehouses and distribution centres are at proximate geographical areas, takes advantage of the potential savings in transportation costs.

The cost breakdown, as shown in Figure 6-5, under all scenarios and during each time period, shows that during the first time period infrastructure cost has the lion share of total SCN's operational cost reaching 60% with production cost and handling cost following in rank order with 25% and 10%, respectively. The remaining 5% is divided to transportation cost (4.50%) and inventory cost (0.50%). During the next time periods cost breakdown presents a constant pattern with production cost approximating 60%, handling cost 25%, transportation cost 14%, and inventory 1%.

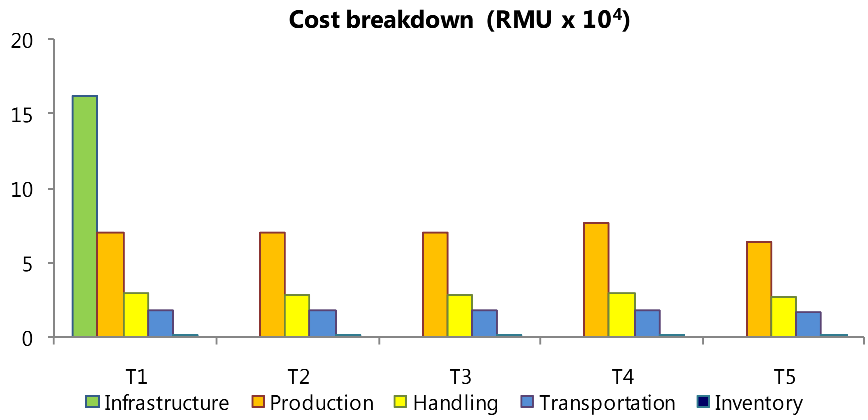


Figure 6-5: Operational costs from model M4

Under all scenarios and at the end of each time period, inventories exhibit a pattern (see Figure 6-6) where all time periods, are high in plants, low in warehouses and minor in distribution centres as a result of safety stock requirements. However, at the end of time period 4 inventories in distribution centres are breaking the afore-mentioned profile.

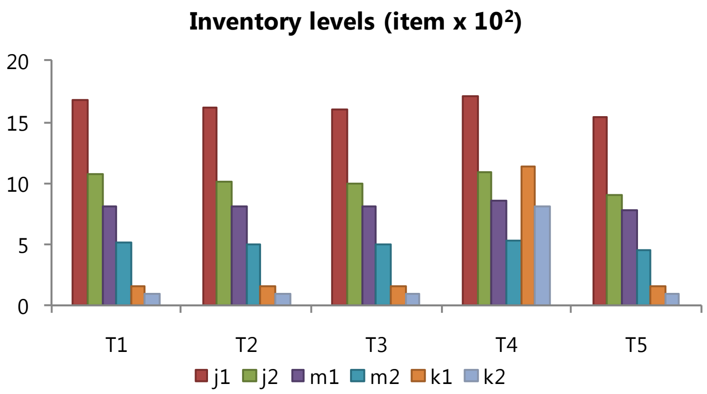


Figure 6-6: Inventory levels from model M4

6.4.3 Evaluation of model M4

An effective decision support model should have, among others features, the ability to adjust its output to different decision makers' preferences and the ability to be in-sensitive to slight variations on input data. In these lines, our model is tested initially under four potential choices of decision makers, expressed in the form of scenarios' realization probabilities, and then under minor deviations on some input parameters.

Moreover, one important aspect of any innovative model is its value in comparison to existing ones. What are the potential benefits of employing the proposed model rather than an existing one? In many cases it is difficult to provide adequate proofs supporting a proposed model, due to the lack of comparison possibilities, and the argumentation is limited to qualitative evidence. On the contrary, if the potential benefit is quantified the model highlights its value and strengthens its prospect. Along these lines, our model is compared with a cost minimisation counterpart SCN design model that ignores the SLB.

Adaptability evaluation

In assessing adaptability, we perform four experiments with the real case study data presented in Section 6.4.1 and by changing the scenarios' realization probabilities. Experiment 1 expresses decision makers' confidence that the four uncertain parameters during the second time period will all be improved, in comparison to precedent time period, whereas experiment 2 expresses the contrary condition where these parameters during the second time period will all be worsened. Experiment 3 expresses decision makers' confidence that the uncertain parameters will follow a constant sign of rate of change, either continuous improvement or continuous worsening, without any deviation from time period to time period whereas experiment 4 expresses decision makers' confidence that these parameters will follow a rapidly shifting sign of rate of change, either improvement-worsening-improvement-worsening or worsening-improvement-worsening-improvement, from time period to time period.

In experiment 1 the probabilities of scenarios 1 to 8 are doubled ($\psi_s = 0.125, \forall\, s = 1, \cdots, 8$) while those of scenarios 9 to 16 are consequently becoming zero ($\psi_s = 0, \forall\, s = 9, \cdots, 16$). The resulting optimal SCN configuration is shown in Figure 6-7 and selects, in comparison to the initial network shown in Figure 6-4, one more warehouse and one more distribution centre.

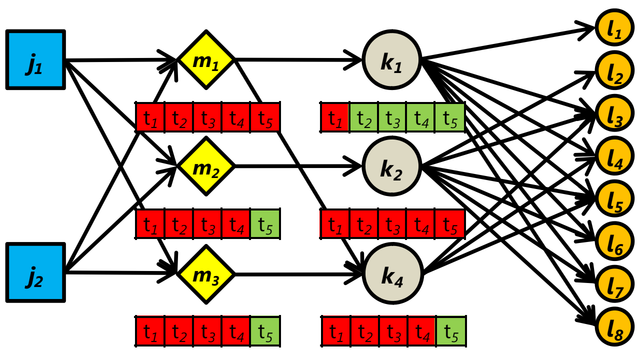


Figure 6-7: Optimal configuration from model M4 under experiment 1

At the end of the first time period the first distribution centre is sold and leased back while at the end of the fifth time period the second warehouse, the third warehouse, and the fourth distribution centre are sold and leased back. Both plants supply products to all established warehouses, the first and the second distribution centre receive products from proximate warehouses while the fourth distribution centre receives products from the first and the third warehouse. The first and the second distribution centre serve the same customer zones as those shown in Figure 6-4 and the fourth distribution centre serves three customer zones.

In experiment 2 the probabilities of scenarios 9 to 16 are doubled ($\psi_s = 0.125, \forall\, s = 9, \cdots, 16$) while those of scenarios 1 to 8 are consequently becoming zero ($\psi_s = 0, \forall\, s = 1, \cdots, 8$). The resulting optimal SCN configuration is shown in Figure 6-8 and selects, in comparison to the initial network shown in Figure 6-4, one more warehouse. At the end of the fifth time period the second warehouse, the third warehouse, and the second distribution centre are sold and leased back. Both plants supply products to all established warehouses, the first distribution centre receives products from its proximate first warehouse and from the third warehouse whereas the second distribution centre receives products only from its proximate second warehouse. The first distribution centre serves all customer zones and the second distribution centre serves the same customer zones as those shown in Figure 6-4.

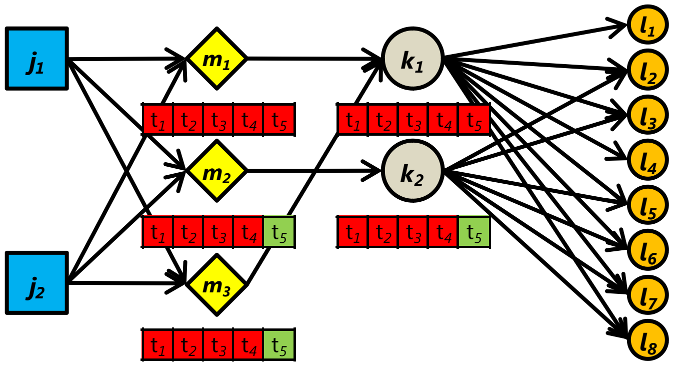


Figure 6-8: Optimal configuration from model M4 under experiment 2

In experiment 3 the probabilities of scenarios 1 and 16 are equal and are totalling unity ($\psi_s = 0.5, \forall\, s = 1, 16$) while those of scenarios 2 to 15 are consequently becoming zero ($\psi_s = 0, \forall\, s = 2, \cdots, 15$). The resulting optimal SCN configuration is shown in Figure 6-9 and selects, in comparison to the initial network shown in Figure 6-4, one more distribution centre. At the end of the fifth time period four sale and lease back deals are decided for all warehouses and distribution centres except the first distribution centre which remains under the ownership of the company. Both plants supply products to all established warehouses, the first distribution centre and the second distribution centre receive products from proximate warehouses while the fourth distribution centre receives products from the first warehouse. The first distribution centre and the second distribution centre serve the same customer zones as those shown in Figure 6-4 and the fourth distribution centre serves three customer zones.

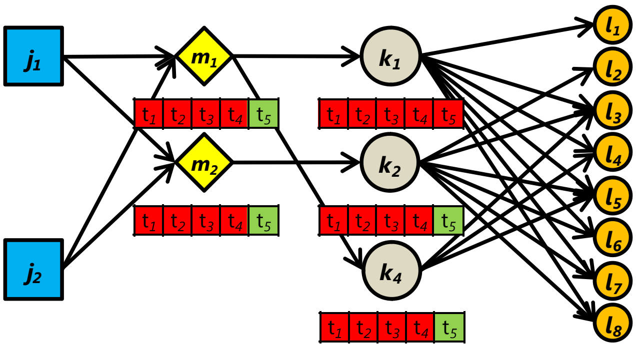


Figure 6-9: Optimal configuration from model M4 under experiment 3

In experiment 4 the probabilities of scenarios 6 and 11 are equal and are totalling unity ($\psi_s = 0.5, \forall s = 6, 11$) while those of all other scenarios are consequently becoming zero ($\psi_s = 0, \forall s = 1, \cdots, 5, 7, \cdots, 10, 12, \cdots, 16$). The resulting optimal SCN configuration is shown in Figure 6-10 and selects, in comparison to the initial network shown in Figure 6-4, one more distribution centre. At the end of the fifth time period the second warehouse and the third distribution centre are sold and leased back. Both plants supply products to all established warehouses, the first distribution centre and the second distribution centre receive products from proximate warehouses while the third distribution centre receives products from the first warehouse. The first distribution centre and the second distribution centre serve the same customer zones as those shown in Figure 6-4 and the third distribution centre serves only its proximate customer zone.

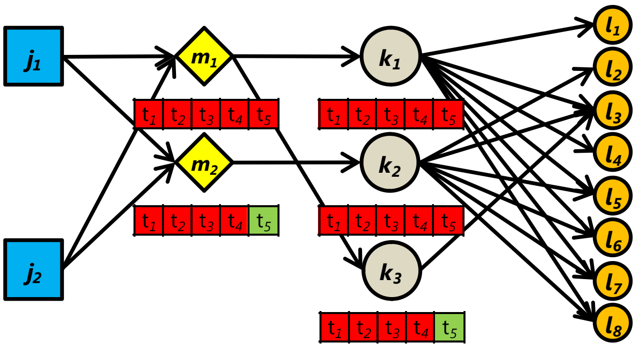


Figure 6-10: Optimal configuration from model M4 under experiment 4

Adaptability evaluation has revealed that the proposed model reacts fairly to different decision makers' preferences by establishing more and several warehouses and distribution centres and by altering their ownership status. A general point on these four configuration variations is the fact that each additional warehouse and/or distribution centre established is sold and leased back and more specifically at the end of time period 5.

Robustness evaluation

In assessing robustness, we perform a sensitivity analysis aiming to investigate whether and how slight changes in some input parameters affect the optimal solution. Eight analyses were conducted based on an equal number of parameters, namely, maximum transported quantity from consecutive echelons (Q_{ijm}^{max}, Q_{imk}^{max}, Q_{ikl}^{max}), minimum transported quantity from consecutive echelons (Q_{jm}^{min}, Q_{mk}^{min}, Q_{kl}^{min}), maximum production capacity (P_{ijt}^{max}), total resource availability (R_{je}), maximum handling capacities (W_m^{max}, D_k^{max}), minimum handling capacities (W_m^{min},D_k^{min}), coefficient relating capacity to inventory (γ_{im}, γ_{ik}), and safety stock policy (δ_{ij}, δ_{im}, δ_{ik}). Each parameter is deviated from its initial value over the range ±20%, by different increments, and then for each one of these variations the model was solved to optimality.

Table 6 shows the results of three sets of outputs, namely, configuration and ownership status, objective function, and inventories. Nodes represent the total number of facilities, plants and customer zones included, while links represent the total number of transportation links and SLB the total number of sold and leased back assets. NOPAT and UPSLB represent the two constituents of the model's objective function while inventories the total number of products stocked in all storing nodes at the end of the planning horizon.

Table 6-38: Sensitivity analysis results

Parameter	*Output*	**Parameter variation***							
		-20%	*-10%*	*-5%*	*-1%*	*+1%*	*+5%*	*+10%*	*+20%*
	Nodes, Links, SLB	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
$Q_{jm}^{max}, Q_{mk}^{max}, Q_{kl}^{max}$ $Q_{jm}^{min}, Q_{mk}^{min}, Q_{kl}^{min}$	*NOPAT, UPSLB*	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc
	Inventories	nc	nc	nc	nc	nc	nc	nc	nc
	Nodes, Links, SLB	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
W_m^{max}, D_k^{max} W_m^{min}, D_k^{min}	*NOPAT, UPSLB*	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc
	Inventories	nc	nc	nc	nc	nc	nc	nc	nc
	Nodes, Links, SLB		nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
P_{ijt}^{max}	*NOPAT, UPSLB*	Infeasible	-0.59%, nc	-0.27%, nc	-0.05%, nc	+0.05%, nc	+0.24%, nc	+0.43%, nc	+0.76%, nc
	Inventories		-0.62%	-0.35%	-0.07%	+0.03%	+0.19%	+0.04%	-1.23%
	Nodes, Links, SLB	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
R_{je}	*NOPAT, UPSLB*	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc
	Inventories	nc	nc	nc	nc	nc	nc	nc	nc
	Nodes, Links, SLB	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
γ_{im}, γ_{ik}	*NOPAT, UPSLB*	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc	nc, nc
	Inventories	nc	nc	nc	nc	nc	nc	nc	nc
	Nodes, Links, SLB	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc	nc, nc, nc
$\delta_{ij}, \delta_{im}, \delta_{ik}$	*NOPAT, UPSLB*	+0.60%, nc	+0.30%, nc	+0.15%, nc	+0.03%, nc	-0.03%, nc	-0.14%, nc	-0.27%, nc	-0.52%, nc
	Inventories	-18.13%	-8.58%	-4.01%	-1.02%	-3.20%	-11.20%	-13.10%	-12.56%

* Initial values: Nodes 14; Links:19; NOPAT: 443,529; UPSLB:19,918; Inventories: 3920
Note: nc means no change

The model is robust to volatility in maximum/minimum transported quantity from consecutive echelons, in maximum/minimum handling capacities, in total resource availability, and in coefficient relating capacity to inventory. Variations in the maximum production capacity cause minor variation in the NOPAT and in the inventory levels while deviations in the safety stock policy cause analogous changes in the inventory levels, but again the changes in NOPAT are minor. It is clear from this analysis that slightly modifying the SCN's restrictions on capacities, availabilities, and requirements can lead to a quantitative variation of the solution, in the case of maximum production and safety stock policy, but the structure of the solution is robust with respect to these variations.

Benefit evaluation

A comparison with a pure cost minimisation model deemed worthy in further highlighting the benefit of the model M4. Initially we solve the following MILP problem, consisted of $\mathrm{OBJ}^{4'}$ and constraints (3.1)–(3.11), (3.15)–(3.24), (3.28)–(3.36), (4.1), and (5.1)–(5.6), using the real case study data presented in Section 6.4.1. This model (M4') ignores the SLB model and aims to minimise the total expected costs occurring in the SCN under all structural and operational constraints.

$$
\begin{aligned}
\mathrm{OBJ}^{4'}: \min \sum_{t=1}^{\frac{EL}{4}} \sum_{s=1}^{2^{\left(\frac{EL}{4}-1\right)}} \psi_s \Bigg(& \underbrace{\sum_{i,j} \mathrm{C}_{ij}^{P} \mathrm{P}_{ijt}^{[s]}}_{\substack{production\\ cost}} - \underbrace{\sum_{i,j,m} \mathrm{C}_{ijm}^{TR} \mathrm{Q}_{ijmt}^{[s]}}_{\substack{transportation\ cost\\ plants\ to\ warehouses}} - \underbrace{\sum_{i,m,k} \mathrm{C}_{imk}^{TR} \mathrm{Q}_{imkt}^{[s]}}_{\substack{transportation\ cost\\ warehouses\ to\\ distribution\ centres}} \\
& - \underbrace{\sum_{i,k,l} \mathrm{C}_{ikl}^{TR} \mathrm{Q}_{iklt}^{[s]}}_{\substack{transportation\ cost\\ distribution\ centres\ to\\ customer\ zones}} - \underbrace{\sum_{i,m} \mathrm{C}_{im}^{WH} \left(\sum_{j} \mathrm{Q}_{ijmt}^{[s]} \right)}_{\substack{handling\ cost\\ warehouses}} - \underbrace{\sum_{i,k} \mathrm{C}_{ik}^{DH} \left(\sum_{m} \mathrm{Q}_{imkt}^{[s]} \right)}_{\substack{handling\ cost\\ distribution\ centres}} \\
& - \underbrace{\sum_{i,j} \mathrm{C}_{ij}^{I} \frac{\mathrm{I}_{ijt}^{[s]} + \mathrm{I}_{ij,t-1}^{[s]}}{2}}_{\substack{inventory\ cost\\ plants}} - \underbrace{\sum_{i,m} \mathrm{C}_{im}^{I} \frac{\mathrm{I}_{imt}^{[s]} + \mathrm{I}_{im,t-1}^{[s]}}{2}}_{\substack{inventory\ cost\\ warehouses}} - \underbrace{\sum_{i,k} \mathrm{C}_{ik}^{I} \frac{\mathrm{I}_{ikt}^{[s]} + \mathrm{I}_{ik,t-1}^{[s]}}{2}}_{\substack{inventory\ cost\\ distribution\ centres}} \Bigg) \\
& + \underbrace{\sum_{m} \mathrm{C}_{m}^{WF} \mathrm{PW}_{m}}_{\substack{establishment\\ cost\\ warehouses}} + \underbrace{\sum_{k} \mathrm{C}_{k}^{DF} \mathrm{PDC}_{k}}_{\substack{establishment\\ cost\\ distribution\ centres}}
\end{aligned}
$$

Then, we solve again our initial MINLP problem M4 by fixing the binary configuration variables (PDC_k, PW_m, PWDC_{mk}, PDCL_{kl}) to the values resulted from the optimal solution of the pure cost minimisation model M4′. The optimal SCN in this case is shown in Figure 6-11 and selects only one warehouse and one distribution centre and does not sale and lease back any of them. The total expected NOPAT is 440,210 RMU and the total expected UPSLB is 0 RMU.

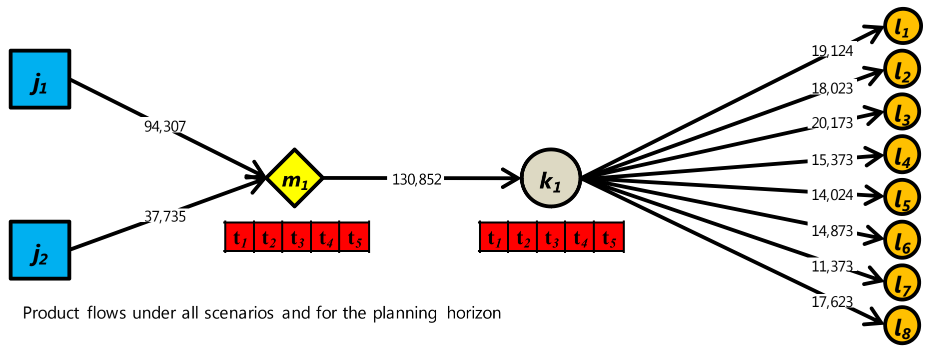


Figure 6-11: Optimal configuration from model M4′ (NOPAT: 440,210 & UPSLB: 0.00)

The cost breakdown (see Figure 6-12), under all scenarios and during each time period, shows the same pattern as in the initial network shown in Figure 6-4 with only exception the infrastructure cost during the first time period where its share is lower (40%), due to the non-existence of the second warehouse and the second distribution centre, with production cost following in rank order with 35%.

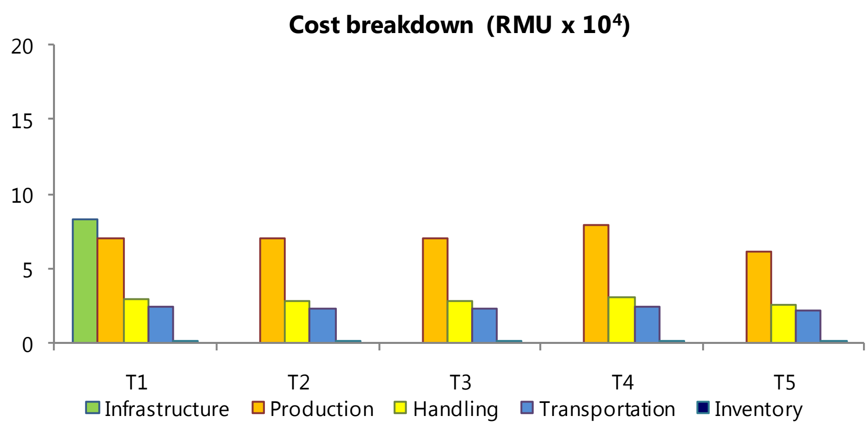


Figure 6-12: Operational costs from model M4′

Under all scenarios and at the end of each time period, inventories exhibit a profile (see Figure 6-13) quite different from that of the initial network shown in Figure 6-4 as inventories in the first warehouse at all time periods are high and at the end of the fourth time period an extremely high level of inventories are stocked in the first distribution centre. Regarding plants, inventories in the first plant are at the same level, compared to inventories of the network shown in Figure 6-4, while in the second plant inventories are on average 25% lower.

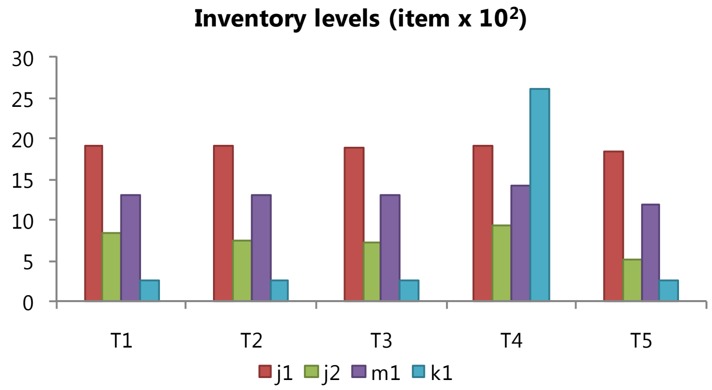
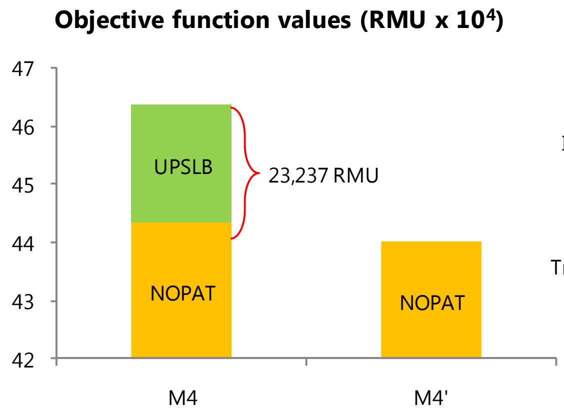


Figure 6-13: Inventory levels from model M4′

A comparison of the objective function values between these two models reveals a loss of 23,237 RMU for the M4′ model, a figure that is equal to a 5% superiority of the initial model M4. Figure 6-14 presents the pairwise comparisons of objective functions values and of operational costs between these models. In the M4′ model the total production cost is slightly higher (+0.56%), the total handling cost is slightly lower (-0.79%), and the total inventory cost is higher (+4.57%). The great difference is on the two remaining costs where the total infrastructure cost is almost half (-49.07%) and the total transportation cost is increased significantly (+32.49%).



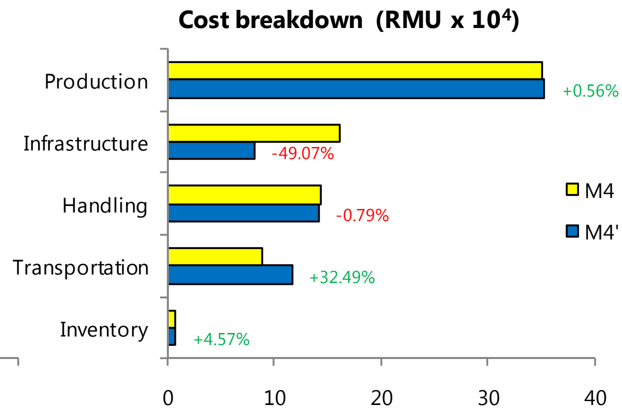


Figure 6-14: Comparison of objective functions values & operational costs between M4 & M4′

The M4′ model has a considerably lower infrastructure cost (-79,500 RMU) because of the one warehouse and one distribution centre that are not established, in comparison to the M4 model's network shown in Figure 6-4, but this burdens transportation cost (+28,620 RMU) as proximity benefits are missed. The total production cost along with the total inventory cost is increased (+2286 RMU) whereas the total handling cost is decreased (-1125 RMU). Moreover, the model M4′ saves (+4822 RMU) from the SLB payment because of the non-established second warehouse but receives loses (-19,918 RMU) from the unclosed UPSLB.

The previously mentioned cost elements' changes in the M4′ model in comparison to the M4 model are not affecting analogously the value of objective function but some modifications should be made in order to find out the net change. Table 6-39 presents the breakdown of the difference between the values of models' M4′ and M4 objective functions. Each cost element has an absolute individual effect but in some cases the net effect on the objective function must take into account the tax deduction benefits. Tax deduction adjustment is made by multiplying the absolute effect with the term $(1 - \mathrm{TR})$.

Table 6-39: Breakdown of models' M4′ & M4 objective function values difference

Cost element		Change (M4 to M4′) Absolute	Change (M4 to M4′) Net on the OBJ	Explanation
Infrastructure	Depreciation of owned assets	-18,025	+12,618	Savings from depreciation for four time periods for the second warehouse and for five time periods for the second distribution centre minus tax deduction benefits
Infrastructure	Depreciation of SLB assets	-2190	+1533	Savings from depreciation for one time period for the second warehouse minus tax deduction benefits
Infrastructure	SLB payments	-4822	+3376	Savings from the unpaid SLB payments minus tax deduction benefits
Infrastructure	UPSLB	-19,918	-19,918	Loses from the unclosed SLB agreement
Production		+1956	-1369	Loses from the higher production cost minus tax deduction benefits
Handling		-1125	+788	Savings from the lower handling cost minus tax deduction benefits
Transportation		+28,620	-20,034	Loses from the higher transportation cost minus tax deduction benefits
Inventory		+330	-231	Loses from the higher inventory cost minus tax deduction benefits
		Total difference	-23,237	

This analysis demonstrates that a pure cost minimisation SCN design model is inferior to the model M4 proposed in this chapter as it is driven by the establishment cost of warehouses and distribution centres and fails to recognise to benefits of a SLB agreement.

6.5 Concluding remarks

In this chapter, our research effort was motivated by the increasing need of SCN managers to have holistic decision support models that track and quantify the financial impact of their production and distribution decision. As the SCN design/redesign/retrofitting is a project that is evaluated during a capital budgeting procedure, where financial management personnel has the main decision role, SCN managers should have stung evidence and figures that their decisions contribute to the value maximisation principle.

On these lines, the proposed MINLP model M4 enables SCN managers to evaluate their strategic decisions on SCN infrastructure configuration and planning through both cost and financial perspectives. To wit, a decision to reject the establishment of a distribution centre in one geographical area due to its high infrastructure cost is myopic if it ignores the real estate market outlook. This expensive distribution centre could add value to the company through a SLB deal and the UPSLB might overcome the drawback of higher establishment cost. In addition to UPSLB, a SLB agreement improves many financial ratios, most notably liquidity ratios, provides tax deduction benefits along with "depreciation shield" advantages, and allows the company to focus on its core mission rather than on the real estate portfolio management. The bottom line, therefore, is to consider the potential of revealing the value shackled in assets when designing a SCN. This is realised via the SLB modelling framework presented and incorporated in model M4.

The model M4 could be incorporated in most of SCN design models as the integration with the SLB modelling is made through binary variables that express the establishment/operation/opening of warehouses and/or distribution centres and exist in any of these models. The data regarding SLB might come from estimations of company's experienced managers along with assistance from professional real estate consultants and specialists. In many cases, the long-term interest rate that banks charge the company for fixed assets investments is used as a surrogate for LIBR while various reference rates in money markets (Euribor, Libor, Fed base rate, etc.) plus a spread are used as a substitute for IRIL.

A real case study was used to illustrate the applicability of our model and further we document its adaptability to several preferences and/or estimations of decision managers', its robustness to slight variations on structural and operational parameters, and its superiority in comparison to a cost oriented counterpart SCN design model. However, due to the non linear nature of our model its computational performance is a potential limitation as increasing the problem size results in longer running times for DICOPT. Large-scale problems deserve further research where efficient decomposition-based and/or alternative solution strategies might be necessary in yielding solutions at reasonable computational times.

Finally, future research might improve our model by developing appropriated solution techniques for large scale problems and further enrich the finance modelling of SCN's with integration of other advanced financial aspects such as forward commodity contracts for marketable raw materials, interest rate and currency swaps as a hedging medium against volatility, and others.

CHAPTER 7

Conclusions & future directions

7.1 Conclusions

The main objective of this work has been to develop mathematical programming decision support models and tools capable of capturing, addressing, monitoring, and optimising various financial issues and aspects, inherent in SCNs, in an integrated manner with sourcing, production, distribution, and inventory operations.

In order to achieve this aim, initially, a generic SCN design model under transient demand uncertainty has been presented in Chapter 3 (Georgiadis, Tsiakis, Longinidis, & Sofioglou, 2011). This MILP model (M1) supports strategic decision making in SCN via optimising network configuration decisions along with production, transportation, and inventory decisions under demand uncertainty. Model M1 served as a background model to next three financial models M2, M3, and M4 as all of which include its mathematical formulation.

Financial statement analysis is the first financial aspect that has been formulated within the SCN design model, in Chapter 4. Financial statement analysis is a widely known methodology in financial management where the financial status, the prosperity, and the potential of a company are assessed. These pillars are very important in providing funds to a company from financial institutions and shareholders. Financial statement analysis is based ratios calculations from accounts presented in the balance sheet and in the income statement and thus these should be mathematically formulated within the proposed MILP model M2 (Longinidis & Georgiadis, 2011). Model M2 employs the SCN design-planning formulation of model M1 and integrates a financial operation and a financial ratios formulation along with an advanced financial objective function, namely EVA. Model M2 supports strategic decision making in SCN via optimising network configuration decisions along with production, transportation, inventory, and financial status decisions under demand uncertainty.

Credit solvency along with advanced financial performance is the second financial aspect formulated within the SCN design model, in Chapter 5. Credit solvency is the measure that overcomes the limitation of which financial ratios are more appropriate to summarise and express a company's economic standing and along with financial performance provides investors a compact, convenient, and easily interpretable picture about a company's prospectus. Although, these two pillars of investment attractiveness are considered together they are not necessary moving to the same direction and underlined trade-offs exist challenging a mathematical formulation capable of expressing them. The proposed moMINLP model M3 captures these trade-offs by integrating the Altman's Z-score and the EVA™ within the core SCN design-planning formulation of model M1 (Longinidis & Georgiadis, 2013). Model M3 assists strategic decision making in SCN by providing a portfolio of optimal network configurations that contain optimal decisions regarding production, transportation, inventory, and financial structure decisions under economic uncertainty.

Sale and leaseback of fixed assets is the third financial aspect integrated within the SCN design model, in Chapter 6. This is an advanced financial management method that improves liquidity, strengthens credit solvency, and provides unearned profits and depreciations shield benefits, through fixed assets. The SCN design project is included in a company's capital budgeting procedure and as such it should be comply with the value maximisation principle in order to be accepted by financial personnel. By integrating this methodology in the MILP SCN design model M4 the strategic decision making process is supported by providing an additional financial tool to SCN managers in their endeavours to argument against other competitive capital budgeting projects.

The main contributions of this Thesis are summarised as follows:

I. A detailed mathematical formulation for the problem of designing SCNs comprising multiproduct production facilities with shared production resources, warehouses, distribution centres and customer zones and operating under time varying demand uncertainty. Uncertainty is captured in terms of a number of likely scenarios possible to materialise during the life time of the network. The problem was formulated as a MILP problem and solved to global optimality using standard branch-and-bound techniques.

II. A mathematical model that integrates financial considerations with SCN design decisions under demand uncertainty. The proposed MILP problem enchases financial statements analysis through financial ratios and demand uncertainty through scenario analysis and solved to global optimality using standard branch-and-bound techniques.

III. A mathematical model that incorporates financial performance and credit solvency, the two essential pillars of financial status capable of providing the necessary capitals to a SCN, with SCN design decisions under economic uncertainty. The proposed moMINLP model enchases financial performance through economic value added (EVA™) and credit solvency through a valid credit scoring model (Altman's Z-Score) and is solved by using standard e-constraint method and branch-and-bound techniques

IV. A mathematical model that integrates advanced financial management methods with SCN design decisions in order to transform fixed assets into the medium that improves liquidity and strengthens credit solvency. The proposed MINLP model integrates SLB technique with location/allocation, sourcing, production, distribution, and inventory decisions under real estate market uncertainty and is solved using standard branch-and-bound techniques.

This portfolio of four decision support models has been implemented into real industrial case studies and its applicability and value has been illustrated.

7.2 Future directions

Financial management is a wide scientific discipline with many applications, approaches, and methodologies. The fact that many of these operations are in strong relation with the basic operations of SCNs gives place for research initiatives and innovations. There are tree directions for future work each of which focusing on different areas. The first concerns the modelling of other financial issues, the second focuses on improving the computational experience of Thesis models, and the third on integrating our financial modelling framework on other emerging SCN design frameworks.

Future financial modelling aspects are the following:

I. Forward/future commodity contracts for marketable raw materials. SCNs facing uncertainties in the prices of raw materials and they are in the need to hedge against these risks. These contracts convey the right to purchase a specified quantity of some commodity at a fixed price on fixed future date.

II. Risk exposure methodologies, such as value at risk (VaR), downside risk, and stress tests in order to quantify the value of the SCN that is under risk provided a specified probability level.

III. Natural hedging of currency and commodity price fluctuations. SCNs are purchasing raw materials and are selling products in a variety of countries with different currencies. Fluctuations in exchange rates put SCN under vulnerability and natural hedging is a risk prophylaxis medium that reduces SCN vulnerability.

Computational efficiency issues could be also considered as part of a future work including:

I. Design of decomposition algorithms based on several procedures utilised in the literature such as Lagrangian relaxation, augmented Lagrangian decomposition and Benders decomposition.

Emerging SCN design frameworks with potential financial integration capabilities are, among others, reverse and closed-loop SCNs and also green SCNs:

I. The concern about environmental protection and the economic benefits of using returned products has spurred an interest in designing and implementing reverse logistics networks and closed-loop SCNs. Recovery and recycling activities, inherent in these SCNs, require huge amount of capital investments in facilities, infrastructure, and equipment. An appropriate financial modelling framework could increase the overall economic value of the SCN and/or specialise on specific operations such as financial assessment of third party logistics providers (3PLs) in an outsourced reverse flow operation, and sale and leaseback of recovery equipment and facilities.

II. Production and transportation activities are significant sources of air pollution and greenhouse gas emissions, issues which have raised concerns on reducing the amount of emissions worldwide. In this respect, SCNs have incorporated in their design and operation various green initiatives such as modelling greenhouse emissions. Greenhouse emission allowances are traded in spot and future markets where emitters facing comparatively low emission abatement costs for achieving the required reductions can sell the surplus emission allowances to those facing higher abatement costs. An appropriate financial modelling formulation could provide a better hedging policy on vulnerabilities raised from fluctuations in emission allowances prices.

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THESIS PUBLICATIONS

A. Journal articles

A4: Longinidis, P., & Georgiadis, M. C. Integration of sale and leaseback in the optimal design of supply chain networks. *Under review in* ***Omega***, (October 2012)

A3: Longinidis, P., & Georgiadis, M. C. 2013. Managing the trade-offs between financial performance and credit solvency in the optimal design of supply chain networks under economic uncertainty. ***Computers & Chemical Engineering***, 48: 264-279.
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A2: Longinidis, P., & Georgiadis, M. C. 2011. Integration of financial statement analysis in the optimal design of supply chain networks under demand uncertainty. ***International Journal of Production Economics***, 129(2): 262-276.
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A1: Georgiadis, M. C., Tsiakis, P., Longinidis, P., & Sofioglou, M. K. 2011. Optimal design of supply chain networks under uncertain transient demand variations. ***Omega***, 39(3): 254-272.
DOI: http://dx.doi.org/10.1016/j.omega.2010.07.002

B. Book chapters

B2: Longinidis, P., Georgiadis, M. C., & Tsiakis, P. 2011. Integration of financial statement analysis in the optimal design and operation of supply chain networks. In E.N. Pistikopoulos, M. C. Georgiadis, & A. C. Kokossis (Eds.), ***Computer Aided Chemical Engineering***, Vol. 29: 1010-1014. Amsterdam: Elsevier.
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B1: Georgiadis, M. C., & Longinidis, P. 2011. Optimal design and operation of supply chain networks under demand uncertainty. In I. Minis, V. Zeimpekis, G. Dounias, & N. Ampazis (Eds.), ***Supply Chain Optimization, Design, and Management: Advances and Intelligent Methods***: 73-108. Hershey, Pennsylvania: IGI Global.
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C. Conferences with referred proceedings

C4: Longinidis, P., & Georgiadis, M. C. Integration of Sale and Leaseback in the Optimal Design of Multi-Echelon Supply Chain Networks, ***IFAC Conference on Manufacturing Modelling, Management, and Control (IFAC MIM '2013).*** Saint Petersburg, Russia, June 19-21, 2013.

C3: Longinidis, P., & Georgiadis, M. C. A mathematical programming approach to supply chain network design with financial considerations, ***2nd International Conference on Supply Chains (ICSC 2012)***. Katerini, Greece, October 05-06, 2012.

C2: Longinidis, P., Georgiadis, M. C., & Tsiakis, P. Integration of financial statement analysis in the optimal design and operation of supply chain networks. In E. N. Pistikopoulos, M. C. Georgiadis, & A. C. Kokossis (Eds.), ***21st European Symposium on Computer-Aided Process Engineering***. N. Marmaras-Chalkidiki, Greece, May 29 - June 1, 2011.

C1: Longinidis, P., & Georgiadis, M. C. Integration of financial statement analysis in the optimal design of supply chain networks under demand uncertainty ***International Conference on Computational Management Science***. Vienna, Austria, July 28-30, 2010.