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Integration of financial statement analysis in the optimal design of supply chain networks under demand uncertainty

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ABSTRACT

Models that aim to optimize the design of supply chain networks have become a mainstream in the supply chain literature. This paper aims to fill a gap in the literature by introducing a mathematical model that integrates financial considerations with supply chain design decisions under demand uncertainty. The proposed Mixed-Integer Linear Programming (MILP) problem enchases financial statement analysis through financial ratios and demand uncertainty through scenario analysis. The applicability of the model is illustrated by using a case study along with a sensitivity analysis on financial parameters expressing the business environment. The model could be used as an effective and convenient strategic decision tool by supply chain managers.

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1. Introduction

During the last decade of the 20th century rapid changes occurred in the business environment. Competition among companies in all their operational functions, from raw material sourcing to customer service, has dramatically increased. Companies have extended their strategic focus in the global market. Cost and price benefits had been scattered across various countries and regions of the world and had pushed companies to seize upon these opportunities. Hence, companies were forced to manage their operations over the limited "unique enterprise" framework. Orientation to external environment is a medium that enables companies to obtain the necessary sources and abilities (Spekman et al., 1998). These developments have driven to the evolution of "supply chain management" (SCM) as companies have realized that they cannot operate individually anymore, but only as parts of a complicated business operations chain (Tan et al., 1998).

Organizations, which constitute a supply chain network (SCN), interact through continuous and two-sided connections that create added value in products (Mentzer et al., 2001). These networks have an undefined number of echelons and stages while their main operations involve purchasing of raw materials from suppliers, production, transportation and storage of products, inventory management, and distribution of products to customers (Simchi-Levi et al., 2000).

Part of the planning process in SCM aims at finding the best possible supply chain configuration. These decisions are considered strategic because of their long time horizon and are tackled with facility location models. However, by considering certain aspects of the supply chain environment, these models are adequately capable to support the Supply Chain Network Design (SCND) phase (Melo et al., 2009). Moreover, dynamic facility location models, where the decisions are spread out over a long-term planning horizon and the decision variables are time-dependent, are becoming more compatible to track the dynamics of complex supply chains (Thanh et al., 2008).

Since companies recognized the potential competitive advantages, gained through a holistic management of their supply chain, the academic community has been developing several models that describe their design and operation. These models support management staff in both strategic and tactical decisions regarding management of supply and distribution networks. Although numerous successful models have been developed for the design and operation of supply chains, their vast majority ignores decisions involving revenues, marketing campaigns, hedging against uncertainties, investment planning, and other corporate financial decisions (Shapiro, 2004). Financial factors are among the issues that have a strong impact on the configuration of global supply chains (Melo et al., 2009). Financial globalization factors such as corporate income taxes, transfer prices, currency exchange rates, are some of the key components that a supply chain design model in the delocalization context should take into account (Hammami et al., 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 (Guillén et al., 2006). Inclusion of financial considerations in supply chain models is particularly advised for capital intensive activities (continuous processes, heavy industrial equipments, etc.).

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Nomenclature

Indices

e production resources (equipment, manpower, utilities, etc.)
i products
j plants
k possible distribution centers
l customer zones
m possible warehouses
s product demand scenario
t time period

Sets

K^{SS} set of distribution centers that should be supplied by a single warehouse
L^{SS} set of customer zones that should be supplied by a single distribution center

Parameters

C_{im}^{WH} unit handling cost for product i at warehouse m
C_{ik}^{DH} unit handling cost for product i at distribution center k
C_{m}^{W} annualized fixed cost of establishing warehouse at location m
C_{k}^{D} annualized fixed cost of establishing distribution center 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 center k
C_{ikl}^{TR} unit transportation cost of product i transferred from distribution center k to customer zone l
C_{ij}^{I} unit inventory cost of product i at plant j
C_{im}^{I} unit inventory cost of product i at warehouse m
C_{ik}^{I} unit inventory cost of product i at distribution center k
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
D_{k}^{max} maximum capacity of distribution center k
D_{k}^{min} minimum capacity of distribution center k
DCMFM days corresponded to material flow measurement scale
$DM_{ilt}^{[s]}$ demand for product i from customer zone l during time period t under scenario 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
$I_{ijt}^{[s],min}$ minimum inventory of product i held in plant j at the end of time period t under scenario s
$I_{imt}^{[s],min}$ minimum inventory of product i held in warehouse m at the end of time period t under scenario s
$I_{ikt}^{[s],min}$ minimum inventory of product i held in distribution center k at the end of time period t under scenario s
$LTDR_t$ 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
n^{DC} minimum inventory held at distribution centers 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
$P_{ijt}^{[s],max}$ maximum production capacity of plant j for product i during time period t under scenario s
$P_{ijt}^{[s],min}$ minimum production capacity of plant j for product i during time period t under scenario s
PMR_t lower bound for profit margin ratio at the end of time period t
$PRICE_{ilt}^{[s]}$ price for 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
Q_{mk}^{min} minimum rate of flow of material that can practically and economically be transferred from warehouse m to distribution center k
Q_{kl}^{min} minimum rate of flow of material that can practically and economically be transferred from distribution center k to customer zone l
$Q_{ijm}^{[s],max}$ maximum rate of flow of product i that can be transferred from plant j to warehouse m under scenario s
$Q_{imk}^{[s],max}$ maximum rate of flow of product i that can be transferred from warehouse m to distribution center k under scenario s
$Q_{ikl}^{[s],max}$ maximum rate of flow of product i that can be transferred from distribution center k to customer zone l under scenario s
QR_t lower bound for quick ratio at the end of time period t
R_{je} total rate of availability of resource e at plant j
$ROAR_t$ 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
W_{m}^{max} maximum capacity of warehouse m
W_{m}^{min} minimum capacity of warehouse m
$WACC_t$ weighed average cost of all invested capital at the end of time period t
ΔT_t duration 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
D_k capacity of distribution center k
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
$I^{[s]}_{ijt}$ inventory level of product i being held at plant j at the end of time period t under scenario s
$I^{[s]}_{imt}$ inventory level of product i being held at warehouse m at the end of time period t under scenario s
$I^{[s]}_{ikt}$ inventory level of product i being held at distribution center k at the end of time period t under scenario s
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
NIS_t new issued stocks
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
$P^{[s]}_{ijt}$ production rate of product i in plant j during time period t under scenario s
PC_t production cost during the time period t
$Q^{[s]}_{ijmt}$ rate of flow of product i transferred from plant j to warehouse m during time period t under scenario s
$Q^{[s]}_{imkt}$ rate of flow of product i transferred from warehouse m to distribution center k during time period t under scenario s
$Q^{[s]}_{iklt}$ rate of flow of product i transferred from distribution center k to customer zone l during time period t under scenario s
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
W_m capacity of warehouse m

Binary variables

PW_m 1 if warehouse m is to be established, 0 otherwise
PDC_k 1 if distribution center k is to be established, 0 otherwise
$PWDC_{mk}$ 1 if material is to be transported from warehouse m to distribution center k, 0 otherwise
$PDCL_{kl}$ 1 if material is to be transported from distribution center k to customer zone l, 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 center 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

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, in new innovative products, and for expansion in new markets. The basic sources of financing are loans from financial institutions and funds from increases in equity stocks, with or without initial public offering (IPO). 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 and Rushinek, 1987). In a similar vein, financial statement analysis enables financial institutions to benchmark companies in the same industry with relative measures instead of absolute measures (Cowen and Hoffer, 1982).

Another important issue in SCM is uncertainty. Demand uncertainty has been early recognized in the SCM context as the essential cause of the "bullwhip effect", which is characterized by excess volatility in demand (Davis, 1993). Uncertainty of customer demand is rarely a consideration in models for supply chain network design (Ballou, 2001) and especially for global logistics systems (Vidal and Goetschalckx, 1997). Systematic consideration of uncertainty can facilitate calculation of expected return and evaluation of associated risks based on current status and future predictions (Papageorgiou, 2009).

This work first and foremost aims to enrich the literature in supply chain network design using mathematical programming techniques. Financial statement analysis and transient demand uncertainty are the salient features of the proposed approach.

The rest of the paper is structured as follows. Section 2 reviews the literature in the field of financial aspects and demand uncertainty within supply chain modeling while Section 3 introduces the supply chain network design problem and presents the mathematical formulation. The applicability of the proposed model is illustrated through a case study in Section 4 and in Section 5 some computational experiments evaluate the model in larger testbeds. Concluding remarks are drawn in the last section along with further research directions.

2. Literature review

2.1. SCM models with financial aspects

Despite the fact that many researchers have mentioned the importance of financial considerations in the SCM context (Shapiro, 2004; Hammami et al., 2008, Melo et al., 2009, Papageorgiou, 2009) very few research contributions can be found in the literature. SCM 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 optimized along with the other SCND variables and those where financial aspects are considered as known parameters used in constraints and in the objective function.

Regarding the first group, the work of Puigjaner and co-workers represents a key contribution in the area. Romero et al. (2003) build a deterministic multi-period mathematical model for the batch chemical process industry (CPI) 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 Mixed-Integer Linear Programming (MILP) model for the batch process industries that integrates advanced planning and scheduling at plant level with cash flow and budgeting. Guillén et al. (2006, 2007) introduced a deterministic MILP model, for a multiproduct, multi-echelon chemical supply chain, which optimizes 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. Recently, Puigjaner and Guillén (2008) 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 supply chain. 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. Yi and Reklaitis (2004) presented a two level parametric optimization 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. Laínez et al. (2007) proposed a deterministic MILP model for the optimal design of a chemical supply chain based on holistic models that covered both the process operations and the finances of the company and aimed at maximizing the corporate value of the firm.

Regarding the second group, Melo et al. (2006) presented a dynamic multi-commodity capacitated facility location model. The model was formulated as a MILP problem that considers simultaneously many practical aspects of SCND while availability of capital investments was the financial aspect incorporated in the model. Tsiakis and Papageorgiou (2008) presented a deterministic MILP model for the optimal configuration of a production and distribution network. The objective was to minimize the total cost across the network and financial constraints for exchange rates and duties were incorporated in the model. Hammami et al. (2009) proposed an SCND model that integrated all the relevant components that characterize 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 supply chain 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 maximizing the expected present value of the net cash in a given planning horizon.

2.2. SCM models under demand uncertainty

SCM models under demand uncertainty have received significant attention in the literature. The body of literature related to these models is extensive. Our review of the literature is indicative and not exhaustive. Interested readers could refer to the literature review works of (a) Snyder (2006) regarding approaches for optimization under uncertainty applied in facility location problems, (b) Taskin and Fuat (2007) about multi-echelon inventory management in supply chains with uncertain demand and lead times, (c) Papageorgiou (2009) regarding systematic consideration of uncertainty within supply chain optimization problems for the process industries, (d) Peidro et al. (2009) for a comprehensive taxonomy of quantitative-based approaches for supply chain planning under uncertainty, and (e) Klibi et al. (2010) regarding SCND problems under uncertainty and the available models proposed to support the design process.

Tsiakis et al. (2001) presented a Mixed-Integer Linear Programming (MILP) model for the optimal design of a multiproduct, multi-echelon SCN under demand uncertainty. This model integrated three distinct echelons within one single mathematical programming formulation and demand uncertainty was introduced with the of scenario analysis. Gupta and Maranas (2003) proposed a two stage stochastic approach in order to model demand uncertainty in planning supply chains from CPI. The supply chain decisions were classified into manufacturing and logistics decisions where the former were made before the realization of the uncertain demand and the latter were postponed. Guillén et al. (2006) introduced a MILP model that addressed the design of chemical supply chains under demand uncertainty. The uncertainty was introduced in this model via scenario-tree analysis while a decomposition strategy, with genetic algorithms and mathematical programming tools, was used to solve the problem due to its large scale. Azaron et al. (2008) develop a robust stochastic programming approach for designing supply chains under uncertainty not only on demands but also on supplies, processing, transportation, shortage, and capacity expansion costs. Their model was multi-objective and the minimization of expected total cost, variance of the total cost, and financial risk were its objectives.

2.3. Literature summary

It is evident from the above literature on SCM models that the integration of financial aspects is mainly focused on scheduling and planning of batch process industries while budgeting and cash flow management are their merely financial considerations. Although cash flow management and capital budgeting are important financial operations, a company should have a holistic competitive financial status. None of the above models formulate the financial status of a company. Moreover, product demand uncertainty is lacking from most of these approaches.

On the other hand, the literature about SCM models under demand uncertainty is rich. Various formulations modeled the demand uncertainty, with scenario or multiperiod approaches and probabilistic approaches being the most popular.

This work aims to fulfill the gap in SCM model with financial aspects by proposing an integrated mathematical programming approach for the optimal design of supply chain network under financial considerations and transient demand uncertainty.

3. Mathematical formulation

3.1. Problem description

The proposed model considers the design of a multiproduct, four-echelon supply chain network as shown in Fig. 1.

In this work, a number of sequential activities occur along these supply chain networks and delineate their 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 supply chain network 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 centers (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 center. In the same manner, each customer zone can be supplied from more than one distribution center.

Across the supply chain network costs are created due to establishment of warehouses and distribution centers, due to production and transportation of materials, and due to handling of materials at warehouses and distribution centers. All these costs have a direct effect on company's published financial statements.

The SCN decisions to be determined by the proposed model are strategic:

(a) The number, location, and capacity of warehouses to be set up.
(b) The number, location, and capacity of distribution centers to be set up.
(c) The transportation links that need to be established in the network.

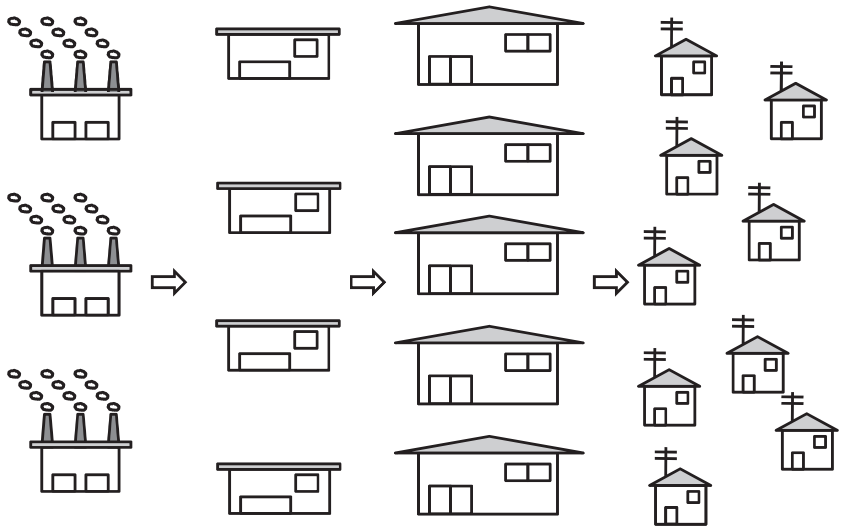

Fig. 1. The supply chain network considered in this study.

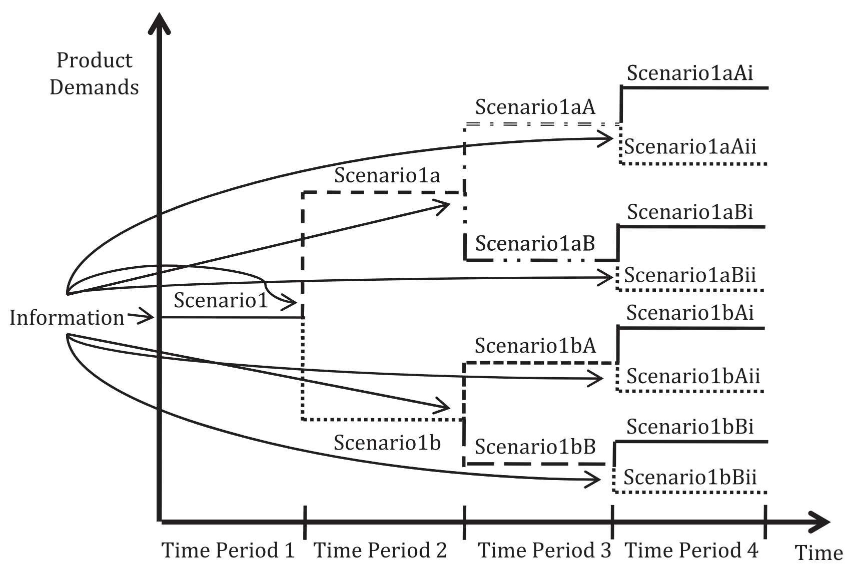

Fig. 2. Scenarios for problems involving both "here-and-now" and "wait-and-see" decisions.

Tactical:

(a) The flows of materials in the network.
(b) The production rates at plants.
(c) The inventory levels at each warehouse.
(d) The inventory levels at each distribution center.

The objective is to maximize the company's shareholder value through the operation of its supply chain network, taking into account several design, operating, and financial constraints.

3.2. Mathematical model

The above problem is formulated through a Mixed-Integer Linear Programming (MILP) problem. The model is dynamic in terms of time-varying uncertain demands. Uncertainty is modeled through a scenario approach and contains both "wait-and-see" and "here-and-now" decisions. In this kind of problems, the information regarding demands in a given period becomes available at the end of the proceeding period and this results in each scenario branch breaking into multiple branches at these points, as shown in Fig. 2.

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). Product demands are assumed to vary as piecewise constant functions of time over a number of time periods of given duration. The uncertainty in these demands is taken into account by postulating a number of scenarios $s=1,\ldots,NS$, each with a potentially different set of piecewise constant demand functions. The proposed model handles any one of these scenarios by multiplying each scenario with its probability to occur ψ_s. These probabilities satisfy the following condition:

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

3.3. Constraints

3.3.1. Network structure constraints

A link between a warehouse m and a distribution center k can exist only if warehouse m also exists:

$$\mathrm{PWDC}_{mk} \le \mathrm{PW}_m \quad \forall m,k \tag{2}$$

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

$$\sum_m \mathrm{PWDC}_{mk} = \mathrm{PDC}_k \quad \forall k \in K^{SS} \tag{3}$$

In any case, if the distribution center does not exist, then its link with the warehouses cannot exist either. This leads to the constraint:

$$\mathrm{PWDC}_{mk} \le \mathrm{PDC}_k \quad \forall m,\ k \notin K^{SS} \tag{4}$$

The previous is applied to those distribution centers that are not single-sourced. For the rest of the distribution centers, constraint (3) already suffices. The link between a distribution center k and a customer zone l will exist only if the distribution center also exists:

$$\mathrm{PDCL}_{kl} \le \mathrm{PDC}_k \quad \forall k,\ l \tag{5}$$

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

$$\sum_k \mathrm{PDCL}_{kl} = 1 \quad \forall l \in L^{SS} \tag{6}$$

3.3.2. Logical constraints for transportation flows

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

$$Q_{ijmt}^{[s]} \le Q_{ijm}^{[s],\max} \mathrm{PW}_m \quad \forall i,j,m,t,s = 1,\ldots,NS \tag{7}$$

Flow of material i from warehouse m to distribution center k can take place only if the corresponding connection exists:

$$Q_{imkt}^{[s]} \le Q_{imk}^{[s],\max} \mathrm{PWDC}_{mk} \quad \forall i,m,k,t,s = 1,\ldots,NS \tag{8}$$

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

$$Q_{iklt}^{[s]} \le Q_{ikl}^{[s],\max} \mathrm{PDCL}_{kl} \quad \forall i,k,l,t,s = 1,\ldots,NS \tag{9}$$

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 constants of the form

$$\sum_i Q_{ijmt}^{[s]} \ge Q_{jm}^{\min} \mathrm{PW}_m \quad \forall j,m,t,s = 1,\ldots,NS \tag{10}$$

$$\sum_i Q_{imkt}^{[s]} \ge Q_{mk}^{\min} \mathrm{PWDC}_{mk} \quad \forall m,k,t,s = 1,\ldots,NS \tag{11}$$

$$\sum_i Q_{iklt}^{[s]} \ge Q_{kl}^{\min} \mathrm{PDCL}_{kl} \quad \forall k,l,t,s = 1,\ldots,NS \tag{12}$$

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

3.3.3. Material balances constraints

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

$$I_{ijt}^{[s]} = I_{ij,t\text{-}1}^{[s]} + \left(P_{ijt}^{[s]} - \sum_m Q_{ijmt}^{[s]} \right) \Delta T_t \quad \forall i,j,t,s = 1,\ldots,NS \tag{13}$$

Constraint (13) states that the available inventory of product i held in plant j at the end of period t (left-hand 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, 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.

In a similar fashion, we formulate the following constraints for the warehouses and distribution centers:

$$I_{imt}^{[s]} = I_{im,t\text{-}1}^{[s]} + \left(\sum_j Q_{ijmt}^{[s]} - \sum_k Q_{imkt}^{[s]} \right) \Delta T_t \quad \forall i,m,t,s = 1,\ldots,NS \tag{14}$$

$$I_{ikt}^{[s]} = I_{ik,t\text{-}1}^{[s]} + \left(\sum_m Q_{imkt}^{[s]} - \sum_l Q_{iklt}^{[s]} \right) \Delta T_t \quad \forall i,k,t,s = 1,\ldots,NS \tag{15}$$

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 centers is assumed to be equal to the corresponding market demand:

$$\sum_k Q_{iklt}^{[s]} = \mathrm{DM}_{ilt}^{[s]} \quad \forall i,l,t,s = 1,\ldots,NS \tag{16}$$

3.3.4. 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:

$$P_{ijt}^{[s],\min} \le P_{ijt}^{[s]} \le P_{ijt}^{[s],\max} \quad \forall i,j,t,s = 1,\ldots,NS \tag{17}$$

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:

$$\sum_i \rho_{ije} P_{ijt}^{[s]} \le R_{je} \quad \forall j,e,t,s = 1,\ldots,NS \tag{18}$$

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.

3.3.5. Capacity constraints for warehouses and distribution centers

The capacity of a warehouse m generally has to lie between given lower and upper bounds, provided, of course that the warehouse is actually established:

$$W_m^{\min} \mathrm{PW}_m \le W_m \le W_m^{\max} \mathrm{PW}_m \quad \forall m \tag{19}$$

$$D_k^{\min} \mathrm{PDC}_k \le D_k \le D_k^{\max} \mathrm{PDC}_k \quad \forall k \tag{20}$$

More specifically, the capacity of a warehouse or a distribution center 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

$$W_m \geq \sum_i \gamma_{im} I_{imt}^{[s]} \quad \forall m,t,s = 1,\ldots,\mathrm{NS} \tag{21}$$

$$D_k \geq \sum_i \gamma_{ik} I_{ikt}^{[s]} \quad \forall k,t,s = 1,\ldots,\mathrm{NS} \tag{22}$$

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 at distribution center k, respectively.

3.3.6. Safety stock constraints

Maintaining a safety stock 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 in case of disruption at one or more of its nodes.

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

$$I_{ijt}^{[s]} \geq I_{ijt}^{[s],\min} \quad \forall i,j,t,s = 1,\ldots,\mathrm{NS} \tag{23}$$

$$I_{imt}^{[s]} \geq I_{imt}^{[s],\min}\,\mathrm{PW}_m \quad \forall i,m,t,s = 1,\ldots,\mathrm{NS} \tag{24}$$

$$I_{ikt}^{[s]} \geq I_{ikt}^{[s],\min}\,\mathrm{PDC}_k \quad \forall i,k,t,s = 1,\ldots,\mathrm{NS} \tag{25}$$

The above constraints ensure that inventory is kept at warehouses or distribution centers only if these are established. We also mention 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 of the corresponding material flows delivered by each plant, warehouse or distribution center node to all other nodes that are served by it. The amount of safety stock to be held at each plant, warehouse or distribution center node is expressed in terms of a given number of days' equivalent of material flow delivered by the node to all nodes supplied by it. In our model we assume that this number of days is the same for all nodes of the same type (e.g. plants, warehouses, or distribution centers). Thus, the safety stock is given by

$$I_{ijt}^{[s],\min} = \frac{n^{\mathrm{P}}}{\mathrm{DCMFM}} \sum_m Q_{ijmt}^{[s]} \quad \forall i,j,t,s = 1,\ldots,\mathrm{NS} \tag{26}$$

$$I_{imt}^{[s],\min} = \frac{n^{\mathrm{W}}}{\mathrm{DCMFM}} \sum_k Q_{imkt}^{[s]} \quad \forall i,m,t,s = 1,\ldots,\mathrm{NS} \tag{27}$$

$$I_{ikt}^{[s],\min} = \frac{n^{\mathrm{DC}}}{\mathrm{DCMFM}} \sum_l Q_{iklt}^{[s]} \quad \forall i,j,k,s = 1,\ldots,\mathrm{NS} \tag{28}$$

where n^{P}, n^{W}, and n^{DC} are the numbers of days equivalent for plants, warehouses, and distribution centers, respectively, and 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). Initial inventories for each product and for each production plant are assumed to been known at a certain level.

3.3.7. Financial operation constraints

The financial cycle of a company is affected by the operations occurred in its supply chain. The results of these operations are presented in the income statement and in the balance sheet. The latter statement is a snapshot of company's wealth and sources through which this wealth was obtained. The basic equation that determines its construction is that the money value of the assets owned by a company is equal to the sum of the money value of shareholders' equity and the money value of debts to third parties. According to double-entry accounting system, every financial transaction changes the three aforementioned components but the basic equation is always satisfied.

The income statement is a dynamic representation of a company's operations during an annually time period. The basic equation that delineates its construction is that the revenues minus the expenses yield the income.

Several constraints need to be introduced to model the financial cycle of the company. Starting from the income statement, we define the (NTS) which is the expected value of the net sales. The following constraint expresses the net sales:

$$\mathrm{NTS}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,l} \mathrm{PRICE}_{ilt}^{[s]} \mathrm{DM}_{ilt}^{[s]} \right) \quad \forall t \tag{29}$$

The cost of goods sold (COGS) constitutes all the expenses realized in order to transform raw materials to products and deliver these products to final customers. In general its constituents are production cost (PC), transportation cost (TC), materials handling cost (HC), and storage cost (SC). Constraints (30)–(34) formulate mathematical all these costs:

$$\mathrm{COGS}_t = \mathrm{PC}_t + \mathrm{TC}_t + \mathrm{HC}_t + \mathrm{SC}_t \quad \forall t \tag{30}$$

$$\mathrm{PC}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,j} C_{ij}^{P} P_{ijt}^{[s]} \right) \quad \forall t \tag{31}$$

$$\mathrm{TC}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,j,m} C_{ijm}^{\mathrm{TR}} Q_{ijmt}^{[s]} + \sum_{i,m,k} C_{imk}^{\mathrm{TR}} Q_{imkt}^{[s]} + \sum_{i,k,l} C_{ikl}^{\mathrm{TR}} Q_{iklt}^{[s]} \right) \quad \forall t \tag{32}$$

$$\mathrm{HC}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,m} C_{im}^{\mathrm{WH}} \left(\sum_j Q_{ijmt}^{[s]} \right) + \sum_{i,k} C_{ik}^{\mathrm{DH}} \left(\sum_m Q_{imkt}^{[s]} \right) \right) \quad \forall t \tag{33}$$

$$\mathrm{SC}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,j} C_{ij}^{\mathrm{I}} \frac{I_{ijt}^{[s]} + I_{ij,t-1}^{[s]}}{2} + \sum_{i,m} C_{im}^{\mathrm{I}} \frac{I_{imt}^{[s]} + I_{im,t-1}^{[s]}}{2} + \sum_{i,k} C_{ik}^{\mathrm{I}} \frac{I_{ikt}^{[s]} + I_{ik,t-1}^{[s]}}{2} \right) \quad \forall t \tag{34}$$

Depreciation (DPR) 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). Constraints (35) and (36) express these calculations:

$$\mathrm{DPR}_t = \mathrm{DR}_t \mathrm{FA}_t \quad \forall t \tag{35}$$

$$\mathrm{EBIT}_t = \mathrm{NTS}_t - \mathrm{COGS}_t - \mathrm{DPR}_t \quad \forall t \tag{36}$$

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) with the short-term interest rate (STR) while the second is the product of long-term liabilities (LTL) with the long-term interest rate (LTR). When the sum of these two expenses is subtracted from EBIT we have the taxable income (TI). This quantity is multiplied with the tax rate (TR) and their product is subtracted from the taxable income yielding the net operating profits after taxes (NOPAT). Constraints (37)–(39) formulate these calculations:

$$\mathrm{IP}_t = \mathrm{LTR}_t \,\mathrm{LTL}_t + \mathrm{STR}_t \,\mathrm{STL}_t \quad \forall t \tag{37}$$

$$\mathrm{TI}_t = \mathrm{EBIT}_t - \mathrm{IP}_t \quad \forall t \tag{38}$$

$$\mathrm{NOPAT}_t = (1-\mathrm{TR}_t)\mathrm{TI}_t \quad \forall t \tag{39}$$

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 (40)–(42) formulate these double entry transactions:

$$\mathrm{NE}_t = \mathrm{NOPAT}_t \quad \forall t \tag{40}$$

$$\mathrm{NC}_t = \mathrm{CFP}_t\mathrm{NOPAT}_t \quad \forall t \tag{41}$$

$$\mathrm{NRA}_t = (1-\mathrm{CFP}_t)\mathrm{NOPAT}_t \quad \forall t \tag{42}$$

Constraint (40) creates a new equity (NE) that is equal to NOPAT. Constraint (41) states that new cash (NC) is generated through one part of the NOPAT whereas constraint (42) states that the remaining part generates new receivable accounts (NRA). In these two constraints cash flow percent (CFP) 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) and current assets (CA) constitute the assets while short-term liabilities (STL) and long-term liabilities (LTL) constitute the debts. This leads to the following constraint:

$$\mathrm{FA}_t + \mathrm{CA}_t = E_t + \mathrm{STL}_t + \mathrm{LTL}_t \quad \forall t \tag{43}$$

The current assets represent the most liquid assets of a company and include cash (C), accounts receivables (RA), and inventory (INR).

$$\mathrm{CA}_t = C_t + \mathrm{RA}_t + \mathrm{INR}_t \quad \forall t \tag{44}$$

Each of balance's sheet accounts is changing during a fiscal year due to financial operations. Regarding fixed assets, the establishment of warehouses and distributions centers increases the money value of this account, through fixed assets investment (FAI), as shown in constraints (45) and (46):

$$\mathrm{FA}_t = \mathrm{FA}_{t-1} + \mathrm{FAI}_t \quad \forall t \tag{45}$$

$$\mathrm{FAI}_t = \sum_m C_m^{\mathrm{W}}\,\mathrm{PW}_m + \sum_k C_k^{\mathrm{D}}\,\mathrm{PDC}_k \quad \forall t \tag{46}$$

The networks' inventory value (INR) in each time period under each demand scenario is measured based on the generally accepted accounting principles (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 (47) illustrates this valuation:

$$\mathrm{INR}_t = \sum_{s=1}^{\mathrm{NS}} \psi_s \left(\sum_{i,j,m,k} C_{ij}^{\mathrm{P}} \left(I_{ijt}^{[s]} + I_{imt}^{[s]} + I_{ikt}^{[s]} \right) \right) \quad \forall t \tag{47}$$

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

$$E_t = E_{t-1} + \mathrm{NE}_t + \mathrm{NIS}_t \quad \forall t \tag{48}$$

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

$$\mathrm{IC}_t = E_t + \mathrm{STL}_t + \mathrm{LTL}_t \quad \forall t \tag{49}$$

3.3.8. *Financial ratios constraints*

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

- Liquidity ratios, which measure the ability of the company to pay its bills over the short run without undue stress. The liquidity ratios used in this model are the current ratio (CUR), the quick ratio (QR), and the cash ratio (CR) defined by constraints (50)–(52), respectively.
- Assets management ratios, which measure how efficiently or intensively a firm uses its assets to generate sales. The asset management ratios used in this model are the fixed assets turnover (FATR), expressed by constraint (53), and the receivables turnover (RTR), expressed by constraint (54).
- Solvency ratios, which measure the firm's long run ability to meet its obligations, or, more generally, its financial leverage. Total debt ratio (TDR), debt–equity ratio (DER), long-term equity ratio (LTDR), and cash coverage ratio (CCR) are the solvency ratios used in this work and expressed by constraints (55)–(58), respectively.
- Profitability ratios, which measure how efficiently the firm uses its assets and how efficiently the firm manages its operations. Profit margin (PMR), defined by constraint (59), return on assets (ROAR), defined by constraint (60), and return on assets (ROER), defined by constraint (61), are the profitability ratios employed in this work.

For each one of the previous ratios, except the three first solvency ratios expressed by constraints (55)–(57), 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. The following 12 constraints present the final form of financial ratios employed in our model:

$$\frac{\mathrm{CA}_t}{\mathrm{STL}_t} \geq \mathrm{CUR}_t \quad \forall t \tag{50}$$

$$\frac{\mathrm{CA}_t - \mathrm{INR}_t}{\mathrm{STL}_t} \geq \mathrm{QR}_t \quad \forall t \tag{51}$$

$$\frac{C_t}{\mathrm{STL}_t} \geq \mathrm{CR}_t \quad \forall t \tag{52}$$

$$\frac{\mathrm{NTS}_t}{\mathrm{FA}_t} \geq \mathrm{FATR}_t \quad \forall t \tag{53}$$

$$\frac{\mathrm{NTS}_t}{\mathrm{RA}_t} \geq \mathrm{RTR}_t \quad \forall t \tag{54}$$

$$\frac{\mathrm{STL}_t + \mathrm{LTL}_t}{\mathrm{FA}_t + \mathrm{CA}_t} \leq \mathrm{TDR}_t \quad \forall t \tag{55}$$

$$\frac{\mathrm{STL}_t + \mathrm{LTL}_t}{E_t} \leq \mathrm{DER}_t \quad \forall t \tag{56}$$

$$\frac{\mathrm{LTL}_t}{\mathrm{LTL}_t + E_t} \leq \mathrm{LTDR}_t \quad \forall t \tag{57}$$

$$\frac{\mathrm{EBIT}_t + \mathrm{DPR}_t}{\mathrm{IP}_t} \geq \mathrm{CCR}_t \quad \forall t \tag{58}$$

$$\frac{\mathrm{NOPAT}_t}{\mathrm{NTS}_t} \geq \mathrm{PMR}_t \quad \forall t \tag{59}$$

$$\frac{\mathrm{NOPAT}_t}{\mathrm{FA}_t + \mathrm{CA}_t} \geq \mathrm{ROAR}_t \quad \forall t \tag{60}$$

$$\frac{\mathrm{NOPAT}_t}{E_t} \geq \mathrm{ROER}_t \quad \forall t \tag{61}$$

3.4. *Objective function*

The objective of the optimization problem is to maximize, for a planning period, a financial figure that expresses the company's net created value. This figure is the Economic Value Added (EVA^{TM}) which is 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 (Stern et al., 1995; Lovata and Costigan, 2002; Ashayeri and Lemmes, 2006). In our model, EVA^{TM} is formulated as follows:

$$\max \sum_{t} (\mathrm{NOPAT}_t - \mathrm{WACC}_t\, \mathrm{IC}_t) \tag{62}$$

where WACC_t is the weighted average cost of capital that express, in general, the opportunity cost of all capitals invested in the company. The optimization problem described by the above objective function and constraints (1)–(61) is a Mixed-Integer Linear Programming (MILP) problem and solved using standard branch-and-bound techniques.

It should be pointed out that although production and distribution aspects in the supply chain network design problem could be decomposed into sub-models (e.g. a model for each echelon in the supply chain), the integration of financial aspects seems to significantly limit potential decomposition opportunities as financial operations are modeled 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.

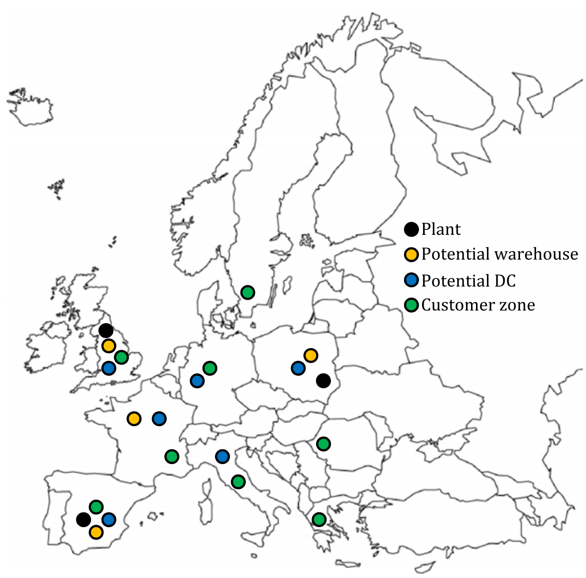

Fig. 3. The case study network.

4. Case study

The applicability of the proposed mathematical model is illustrated through a real case study from a UK multinational company which operates in the foods, home and personal care industry. For confidentiality reasons the company is referred as company Alpha the locations of plants/warehouses/distribution centers/customer zones are referred with numbers and the relative money units have substitute the real currency units.

Company Alpha during its four year strategic planning process, evaluates its current network structure aiming to select the optimal network configuration that attributes a competitive advantage in terms of cost, service quality, and shareholder value creation. The planning horizon of interest is comprised of four 1-year time periods. Company Alpha has three plants in three different European countries and customers in eight different European countries, as shown in Fig. 3. In order to service the whole market, company Alpha considers the establishment of a number of warehouses and distribution centers in four and, respectively, six candidate European countries.

4.1. 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 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 2. The minimum production capacity is assumed to be zero while minimum rate of flow of material that can practically and economically be transferred to each warehouse is equal to 100.

Each plant generates costs because of production, storage, and transportation of products to warehouses. Table 3 presents the unit production and storage cost in each plant, whereas Table 4 provides the unit transportation cost from plants to potential warehouses.

Table 2
Maximum production capacity.

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

Table 1
Utilization and availability data for shared manufacturing resources.

Plant	Resource	Share equipment utilization coefficient (h/ton)							Resource availability (h/year)
		Product							
		P1	P2	P3	P4	P5	P6	P7	
	E1	0.2381	0	0.000	0.000	0.7936	0	0	120
PL1	E2	0	0.0463	0.0617	0.0694	0	0	0	105
	E3	0	0	0	0	0	0	0.1634	105
	E1	0.2178	0	0.3742	0	0	0	0	105
PL2	E2	0	0	0	0.0793	0.1054	0.1582	0.1582	105
	E3	0	0.0740	0.1000	0	0	0	0	105
	E1	0	0	0.1976	0.2222	0	0	0	120
PL3	E2	0	0	0	0	0.7789	0.3968	0.3968	165
	E3	0.1200	0.1543	0	0	0	0	0	120

Table 3
Production and storage costs at plants.

Products	Production (rmu[a]/ton)			Storage (rmu/ton)		
	PL1	PL2	PL3	PL1	PL2	PL3
P1–P6	61.27	59.45	61.44	8.25	8.55	8.98
P7	256.90	268.50	270.80	8.25	8.55	8.98

[a] rmu: relative money unit.

Table 4
Transportation cost from plants to warehouses (rmu/ton).

Plant	Product	Warehouse			
		PW1	PW2	PW3	PW4
PL1	P1–P6	1.24	58.56	62.30	26.16
	P7	1.35	63.46	67.51	28.35
PL2	P1–P6	60.82	1.68	70.96	43.93
	P7	82.70	2.29	96.48	59.72
PL3	P1–P6	76.16	79.21	1.52	54.83
	P7	94.90	98.69	1.80	68.32

Table 5
Infrastructure, material handling, and storage costs at candidate warehouses.

Warehouse	Infrastructure (rmu/year)	Material handling (rmu/ton)	Storage (rmu/ton)
PW1	10,000	4.25	8.25
PW2	5000	4.55	8.55
PW3	4000	4.98	8.98
PW4	6000	4.93	8.93

Table 6
Transportation cost from warehouses to distribution centers (rmu/ton).

Warehouse	Product	Distribution center					
		PDC1	PDC2	PDC3	PDC4	PDC5	PDC6
PW1	P1–P6	0	74.40	76.13	25.96	69.21	29.41
	P7	0	75.28	77.03	26.26	70.02	29.76
PW2	P1–P6	58.85	0	62.96	45.16	109.49	39.80
	P7	60.87	0	65.12	46.71	113.25	42.20
PW3	P1–P6	72.83	76.14	0	49.66	94.35	99.32
	P7	90.75	94.88	0	61.88	117.57	123.76
PW4	P1–P6	28.54	62.78	57.08	0.00	87.52	58.98
	P7	28.88	63.54	57.77	0.00	88.58	59.69

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.

4.2. 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 5. All warehouses are assumed to have a maximum and a minimum material handling capacity of 14,000 tons/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 6 presents the unit transportation cost from potential warehouses to distribution centers. 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 center is equal to 100.

4.3. Distribution centers

The establishment of a distribution center requires an infrastructure cost. Moreover, the operation of the distribution center is associated with material handling costs and storage costs. Details on these costs are presented in Table 7. All distribution centers are assumed to have a maximum and a minimum material handling capacity of 7000 tons/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 8 presents the unit transportation cost from potential distribution centers to each customer zone. Distribution centers 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.

4.4. Customer zones

For the first time period product demands for the eight customer zones are given in Table 9. In the next time period uncertainty is becoming more discernible so two predictions are made for this period's demands (tables are available upon request). In an analogous manner, each one of the second period's demand predictions leads to two distinct demand predictions for the third time period. Therefore, a total of four distinct demand predictions were made for the third time period. Finally, each one of the demand predictions for the third period leads to two distinct demand predictions for the fourth time period (tables are available upon request). Therefore, a total of eight distinct demand predictions were made for the fourth time period. Overall, we consider eight distinct scenarios organized in an analogous tree structure of the type shown in Fig. 2. All scenarios are assumed to have an equal probability to occur.

Table 7
Infrastructure, material handling, and storage costs at candidate distribution centers.

Distribution center	Infrastructure (rmu/year)	Material handling (rmu/ton)	Storage (rmu/ton)
PDC1	10000	4.25	8.25
PDC2	5000	4.55	8.55
PDC3	4000	4.98	8.98
PDC4	6000	4.93	8.93
PDC5	6500	4.85	8.85
PDC6	4000	3.90	6.90

Table 8
Transportation cost from distribution centers to customer zones (rmu/ton).

Plant	Product	Customer zone							
		CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
PDC1	P1–P6	0	75.61	54.51	12.30	70.34	29.89	17.58	119.57
	P7	0	73.12	52.71	11.90	68.02	28.90	17.00	115.63
PDC2	P1–P6	73.55	0	78.68	73.55	136.84	87.23	83.81	118.02
	P7	73.20	0	78.31	73.20	136.20	86.82	83.42	117.47
PDC3	P1–P6	73.28	76.61	19.96	49.96	94.93	99.93	63.28	83.30
	P7	81.65	85.36	24.96	55.67	105.78	111.34	70.52	88.25
PDC4	P1–P6	26.58	58.47	53.16	3.29	81.51	54.93	30.12	79.23
	P7	24.76	54.48	49.53	3.89	75.95	51.18	28.06	72.46
PDC5	P1–P6	77.16	154.33	109.96	84.88	7.15	90.67	59.80	136.97
	P7	77.52	155.04	110.47	85.27	7.98	91.09	60.08	137.60
PDC6	P1–P6	27.08	84.65	79.57	38.93	79.57	17.42	42.32	143.90
	P7	32.65	102.06	95.93	46.94	95.93	18.06	51.03	173.50

Table 9
Product demands from customer zones for time period 1 (scenarios 1–8).

Product	Demands (ton/year)							
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
P1	18.00	0	0	15.00	0	0	0	0
P2	0	499.00	155.00	0	0	0	14.00	0
P3	0	155.00	0	126.00	92.00	0	0	0
P4	506.00	203.00	166.00	0	0	0	40	45.00
P5	0	76.00	0	0	0	0	0	0
P6	452.00	0	66.00	0	0	68.00	0	23.00
P7	0	30	17.00	5.00	0	0	0	0

Table 10
Price of products for each customer zones for time period 1.

Product	Price (rmu/ton)							
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8
P1	250	0	0	230	0	0	0	0
P2	0	240	230	0	0	0	270	0
P3	0	270	0	230	250	0	0	0
P4	440	430	460	0	0	0	410	440
P5	0	230	0	0	0	0	0	0
P6	420	0	430	0	0	400	0	430
P7	0	610	600	600	0	0	0	0

Table 11
Balance sheet at the beginning of planning period.

Account	Values in thousand rmu
Assets	**500**
Tangible Assets	500
Intangible assets	0
Current assets	**1979.088**
Cash	550
Receivable accounts	50
Inventory	1379.088
TOTAL ASSETS	**2479.088**
Equity	**1129.088**
Common stock	1129.088
Retained earning	0
Debt	**1350**
Short term liabilities	450
Long term liabilities	900
TOTAL DEBT and EQUITY	**2479.088**

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. Table 10 presents these prices for the first time period (tables with prices for the other time periods are available upon request).

4.5. Financial operation

At the beginning of the planning horizon company Alpha has a balance sheet shown in Table 11. The financial operation parameters are given in Table 12, whereas the targeted financial ratios, in the form of acceptable bounds, are shown in Table 13 (see constraints (50)–(61)).

4.6. Results

The proposed financial model (FM) was solved using ILOG CPLEX 11.2.0 solver incorporated in GAMS 22.9 software. The model consisted of 44,020 linear 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. Table 14 shows the optimal configuration of the network. The three two-way subtables show the flow from each node (first column) to each sequential node for the planning period and under all scenarios.

The optimal network structure is consisted of four warehouses and three distribution centers. The total created shareholder value is 1,756,627 relative money units (rmu). The total cost related to non-financial operations is 4,010,301 rmu and the transportation cost is its major contributor with 66% share whereas the storage cost is its minor contributor with 2%. All plants supply products to all warehouses. The distribution centers 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

Table 12
Financial cycle parameters for each time period.

Financial parameter	Time period			
	T1	T2	T3	T4
Depreciation rate, DR	0.250	0.250	0.250	0.250
Short term interest rate, STR	0.035	0.040	0.045	0.050
Long term interest rate, LTR	0.070	0.075	0.080	0.085
Tax rate, TR	0.200	0.225	0.250	0.275
Coefficient connecting profits to cash, CFP	0.600	0.600	0.600	0.600
Weighted average cost of capital, WACC	0.015	0.020	0.025	0.030

Table 13
Bounds for financial ratios.

Financial ratio	Target
Current ratio, CUR	2.000
Quick ratio, QR	1.250
Cash ratio, CR	1.000
Fixed assets turnover ratio, FATR	1.100
Receivables turnover ratio, RTR	1.670
Total debt ratio, TDR	0.600
Debt–equity ratio, DER	1.500
Long term debt ratio, LTDR	0.800
Cash coverage ratio, CCR	5.000
Profit margin ratio, PMR	0.050
Return on assets ratio, ROAR	0.010
Return on equity ratio, ROER	0.020

Table 14
Optimal solution for financial model (FM).

	W1	W2	W3	W4		DC1	DC2	DC3	DC4	DC5	DC6
PL1	1685	971	1678	1784	W1		1211			1349	
PL2	481	1038	523	1383	W2		876			1818	
PL3	419	744	945	1019	W3		1819			1263	
					W4	1576	893			1608	
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8			
DC1								1544			
DC2				2018	1239		1443				
DC3											
DC4											
DC5	1351	1516	1630			1416					
DC6											
Economic value added				**1,756,627**							
Production cost				919,976		23%					
Total handling cost				117,674		3%					
Total transportation cost				2,658,482		66%					
Total infrastructure cost				242,000		6%					
Total storage cost				72,169		2%					
Total cost				**4,010,301**							

customer zone is supplied by only one distribution center as shown in Table 14.

4.7. Financial sensitivity analysis

In this part of our work we test the performance of the proposed financial model (FM) 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 supply chain managers to assess how the network will change in cases of economic activity deviations.

One important financial parameter is the weighted average cost of capital (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 15 presents the reaction of the proposed financial model (FM) to various changes in these parameters ranging from −15% to +15%. For brevity, we did not report the product flows from one node to the other. Changes in the WACC, LTR, and STR change only the EVA index but not the configuration of the network whereas changes in CFP and TAXRATE alter the configuration of the network, as shown in Table 15.

Table 15
Financial sensitivity analysis on financial model (FM).

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 centers, we can see that while CFP is decreasing the transportation connections from warehouses to distribution centers are decreasing and thus the network is less complicated. On the other hand, 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 centers. The total amount of flow transported from each warehouse to each distribution center for the planning period and under all scenarios is changing in all the cases reported in Table 15.

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

Table 16
Optimal solution for non-financial model (NFM).

	W1	W2	W3	W4		DC1	DC2	DC3	DC4	DC5	DC6
PL1	6116	400	400		W1	6851					
PL2	400	1468	400		W2	693	1538				
PL3	400	400	2439		W3			3207			
					W4						
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ6	CZ7	CZ8			
DC1	1351			2018	1239	1416	1443				
DC2		1516									
DC3			1630					1544			
DC4											
DC5											
DC6											
Economic value added				**534,988**							
Production cost				904,092		50%					
Total handling cost				110,894		6%					
Total transportation cost				562,665		31%					
Total infrastructure cost				152,000		9%					
Total storage cost				72,169		4%					
Total cost				**1,801,820**							

4.8. Comparison with a non-financial model

Integration of financial statement analysis is the main novelty of our model. Hence, it is deemed worthy to evaluate its contribution by comparing the results of our proposed model (FM) with a model (NFM) that ignores financial statement analysis. Both models have the same objective function (EVA maximization) but the NFM ignores constraints (50)–(61). Table 16 presents the optimal configuration of the network for the NFM and Figs. 4 and 5 present the comparison of the liquidity and profitability ratios' optimal values between the FM and the NFM.

NFM is less complicated because it does not select the fourth warehouse and also selects the three distribution centers that are closed to the three warehouses. It decreases the number of transportation links and simultaneously it increases the flow between warehouses and distribution centers. This configuration is driven by the minor transportation cost between these nodes and is reflected in the transportation cost figure of the NFM which is almost 20% of the transportation cost of the FM (see Table 14). Moreover, the total cost of the NFM network is almost 50% of the FM's total network cost.

However, this advantage is not reflected in the EVA index where the FM creates triple value for shareholders compared to NFM. The main reason for this is the financial operation of a company. EVA index is affected by the net operating profits after taxes (NOPAT) and by total invested capital (IC). 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 (see constraints (16) and (29)). 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 noneffective financial decisions from the NFM explain this phenomenon.

A more illustrative explanation of the FM's superiority is shown in Figs. 4 and 5. Fig. 4 shows how liquidity ratios are formulated for both models at each time period and it is evident that the FM is performing greatly better than the NFM in all individual ratios. In assets management ratios the NFM is performing slightly better than the FM. In solvency ratios, the main drawback of the NFM is evident. The NFM decides to finance its operations with external funds from capital markets (almost 90% of its IC) and increases substantially its liabilities and its paid interest. In contrast, the FM 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

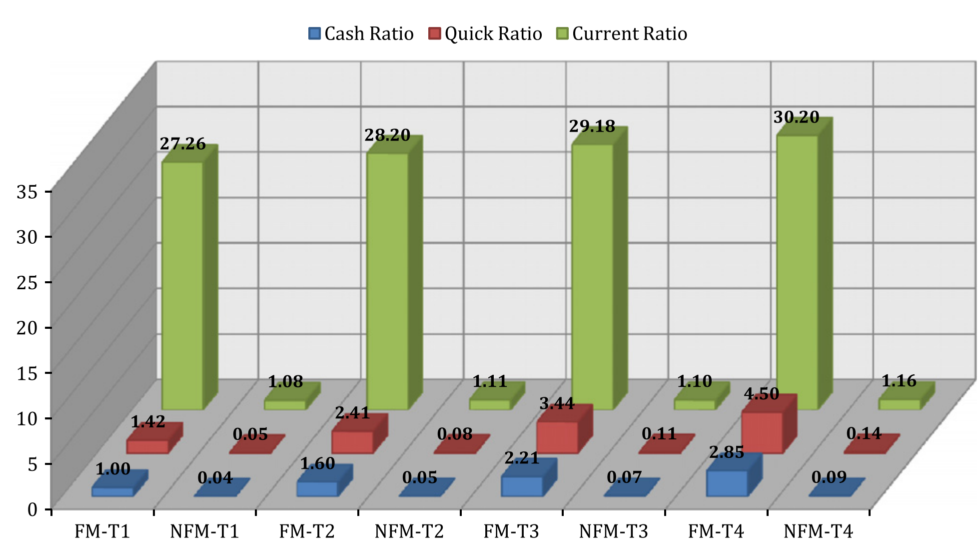

Fig. 4. Liquidity ratios of models FM and NFM for each time period.

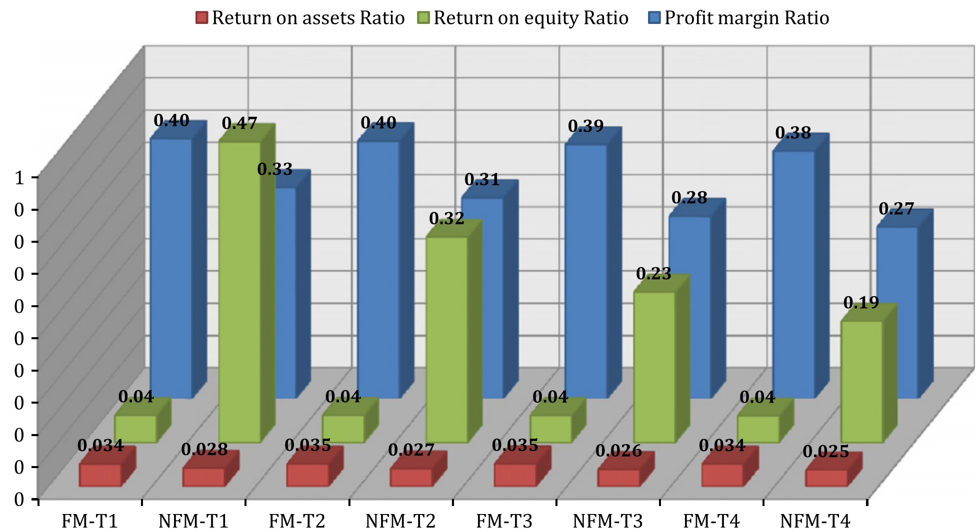

Fig. 5. Profitability ratios of models FM and NFM for each time period.

Table 17
Computational results.

IN	PL	*W*	DC	CZ	*P*	*T*	*S*	CV	DV	LC	Time (s)	
											FM	NFM
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 centers, CZ = customer zones, *P* = products, *T* = time periods, *S* = scenarios, CV = continuous variables, DV = discrete variables, and LC = linear constraints.

markets. Fig. 5 shows the tradeoff between the models. The profitability ratio return on equity (ROE) is extremely high for the NFM in contrast to the FM's 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.

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 8 computational experiments for 8 randomly generated instances, in order to evaluate our model's reaction to larger testbeds. Reaction is evaluated in terms of feasibility and computational times. Table 17 shows the results of these tests. Instances 1 and 2 are increasing the number of time periods and demand scenarios. Instances 3–8 are increasing the number of products, plants, warehouses, distribution centers, and customer zones.

The above results indicate that proposed integrated modeling 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 distributions centers. In this case special solution techniques should be investigated.

6. Conclusion

This work presents a model that integrates financial statement analysis and product demand uncertainty in the optimal design of SC networks. 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 modeling of demand uncertainty through scenarios gives SC managers the ability to weight their demand forecasts, by assigning occurring possibilities on each scenario. With the same manner, SC managers could correct their wrong forecasts, which might be due to unreliable forecasting techniques or due to dramatic economic changes in the marketplace. The modeling of financial statements enables SC managers to take holistic decisions without underestimating the basic objective of a profit company, which is the creation of value for shareholder. 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 supply chain network. It was illustrated how financial considerations affect the optimal structure and operation of the network and the superiority of the model against a nonfinancially constrained model.

As supply chains 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 supply chain in terms of money value associated with its financial operation. After the financial operation is optimized the solution should be used to optimize 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 modeling aspects. Current work focuses on the incorporation of issues related to: product portfolio theory, game theory, future contracts, sell and leaseback techniques, and hedging against risks.

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