

Chapter 2

Financial Issues in the Design of Supply Chains

Abstract Traditionally, approaches available to address the design and operation of supply chains concentrate on the process operations side and neglect the financial part of the problem. In this chapter, a framework whose main focus is the inclusion of financial considerations at the strategic decision-making level is presented. The approach adopts the corporate value of the firm as the performance metric to be maximized, and also evaluates the feasibility of the strategic decisions from the financial point of view by ensuring liquidity control. The main advantages of the new approach presented, which takes into account the incorporation of financial issues, are highlighted by means of a motivating retrofit case study, whose solution is compared with the conventional treatment of the problem. It is shown that the integrated solution ensures the feasibility of the strategic financial decisions and offers superior economic performance, due to its greater ability to create value for the company.

2.1 Integrating Process Operations and Finances

Nowadays, business environment calls for a greater awareness among managers of the financial dimension of decision-making. Recent advances in PSE have focused on devising enterprise-wide modeling and optimization strategies that integrate decisions of different business functions into a global model. Nevertheless, despite the effort made in this topic, most models developed to date focus on the process operations side and ignore decisions involving investment planning, corporate financial decisions, as well as marketing campaigns, and many others aspects of enterprise planning related to the management of the supply chain (Shapiro 2004). Traditionally, the overall problem is addressed in a sequential fashion through the optimization of traditional Key Performance Indicators. The use of these traditional sequential procedures is mainly motivated by the functional organizational structure of firms. Nowadays, companies still have separate departments for production, supply, logistics, service to customers, among others. In an environment like this, the plan of each functional area is considered sequentially as input to the others according to a hierarchy. Thus, the models supporting the decision-making operate

in an isolated way. They optimize partial sets of decision variables, but they do not lead to actual integration of relationships despite promoting the sharing of information between different business entities Romero et al. (2003). This partitioning of decision-making in companies has been reflected in the goals of the studies and the optimization models developed to support them.

The supply chain models currently applied usually assist practitioners in determining the location of the facilities embedded in the network, as well as the tasks that should be accomplished at each moment in order to optimize a given criteria. Moreover, a large proportion of these models optimize costs, profit or NPV. Table 2.1 shows the results of a review of a small sample of works in the PSE field to analyze the Key Performance Indicators (KPI) so far applied in modeling the supply chain. As can be seen, profit and cost have been the most exploited indicators. Such models are useful but no longer enough. They are not sufficient to help companies create and maintain a competitive advantage. To this end, the models should include the sustainable creation of value as objective (Klibi et al. 2010), which requires including as part of their scope financial as well as operation planning decisions.

Importantly, a key component in financial modeling is the effective control of cash. Its steady and healthy circulation throughout the entire business operation has repeatedly been shown to be the basis of business solvency (Howard and Upton 1953). Indeed, the availability of cash governs the production decisions taken in a company. For this reason, models of operations of the supply chain should not consider cash as an infinite resource. A production plan cannot be implemented if it violates the minimum cash flow imposed by the firm (i.e., if the amount of raw materials and/or utilities required cannot be purchased due to a temporary lack of cash).

Consequently, supply chain managers should extend their analysis to include the financial implications of their decisions, which also leads to the utilization of the more comprehensive objective of maximizing the firm's value as opposed to the common optimization of traditional KPIs such as cost or profit. Calculating the firm's value involves a number of complex issues, although there is consensus, as to Buffet's view, that the valuation of a business is determined by the discounted free cash flows occurring from its operation over its lifetime (Buffet 1994). Therefore, the challenge faced by SC managers, who are seeking to enhance corporate value, is to identify supply chain strategies that improve free cash flow generation.

Fact-based strategic planning is increasingly desired and pursued by firms, but many issues remain about how to do it (Shapiro 2004). Optimization models seem to offer an appealing framework for supporting corporate financial decisions, as well as for integrating them with process operation decisions (Shapiro 2006). Currently, with the recent advances in optimization theory and software applications there is no apparent reason why models for SCM that merge concepts from diverse areas of the firm cannot be constructed.

This chapter proposes a general framework for the design of SCs based on the development of holistic models, which cover two areas of the company, the process

Table 2.1 Supply Chain Models for the CPI

Authors	Performance measures																		
	Economic basis								Customer service basis			Efficiency basis				Environmental basis			
	Dividend	Net revenue	Profit	Cost	NPV	Risk	Equity	CSL	Earliness	Tardiness	Inventory level	Makespan	Setup	Cleanup	Facilities utilization	Material consumption	Energy consumption	Waste generation	Eco-indicator 99
Ahmed and Sahinidis (1998)			✓																
Applequist et al. (2000)			✓			✓													
Berning et al. (2002) ^a									✓	✓	✓	✓	✓	✓					
Badell et al. (2004)	✓	✓	✓				✓												
Bok et al. (2000)			✓																
Cakravastia et al. (2002)				✓						✓									
Chen and Lee (2004)			✓					✓			✓								
Fandel and Stammen (2004)			✓																
Gjerdrum et al. (2001)			✓																

(continued)

Table 2.1 (continued)

Authors	Performance measures																		
	Economic basis							Customer service basis			Efficiency basis				Environmental basis				
	Dividend	Net revenue	Profit	Cost	NPV	Risk	Equity	CSL	Earliness	Tardiness	Inventory level	Makespan	Setup	Cleanup	Facilities utilization	Material consumption	Energy consumption	Waste generation	Eco-indicator 99
Guillén-Gosálbez et al. (2005a, 2006a, b)					✓	✓	✓	✓	✓										
Gupta and Maranas (2003)				✓															
Gupta et al. (2000)				✓															
Hugo and Pistikopoulos (2005)					✓														✓
Iyer and Grossmann (1998)					✓														
Ryu et al. (2004)				✓															
Jung et al. (2004)				✓															
Kallrath (2002)		✓	✓	✓															
Lababidi et al. (2004)				✓															
Lasschuit and Thijssen (2004)				✓															

(continued)

Table 2.1 (continued)

Authors	Performance measures																		
	Economic basis							Customer service basis			Efficiency basis				Environmental basis				
	Dividend	Net revenue	Profit	Cost	NPV	Risk	Equity	CSL	Earliness	Tardiness	Inventory level	Makespan	Setup	Cleanup	Facilities utilization	Material consumption	Energy consumption	Waste generation	Eco-indicator 99
Lee et al. (2000)			✓																
Liu and Sahinidis (1996)					✓														
Mokashi and Kokossis (2003)				✓															
Neiro and Pinto (2004)			✓																
Oh and Karimi(2004)					✓														
Papageorgiou et al. (2001)					✓														
Perea-López et al. (2003)			✓																
Romero et al. (2003)	✓																		
Sabri and Beamon (2000)				✓				✓											

(continued)

Table 2.1 (continued)

Authors	Performance measures																		
	Economic basis						Customer service basis			Efficiency basis				Environmental basis					
	Dividend	Net revenue	Profit	Cost	NPV	Risk	Equity	CSL	Earliness	Tardiness	Inventory level	Makespan	Setup	Cleanup	Facilities utilization	Material consumption	Energy consumption	Waste generation	Eco-indicator 99
Seferlis and Giannelos (2004)				✓															
Shulz et al. (2005)			✓																
Sundaramoorthy and Karimi (2004)			✓																
Tsiakis et al. (2001)				✓															
Türkay et al. (2004)				✓															
Wan et al. (2005)				✓															
Zhou et al. (2000)			✓					✓							✓	✓	✓	✓	

^a The objective function is a weighted sum of performance measures indicated in the Table

operations and the finances. To achieve this goal a mathematical formulation, which utilizes mixed integer modeling techniques and merges variables and constraints belonging to each of the abovementioned disciplines, is derived. The presented strategy considers the financial performance as a design objective, and not merely as a constraint on operations. The corporate value (CV) of the firm is adopted as the objective to be maximized as an alternative to the commonly used profit or cost. The resulting model can be used as a decision-support tool for strategic planning. The main advantages of this approach are highlighted through a case study in which the integrated strategy is compared with the traditional approach that computes the maximum profit or net present value (NPV) design without financial considerations.

2.2 Problem Statement

The intent of the supply chain network design problem is typically to determine the optimal manufacturing and distribution network for the entire product line of a company. The most common approach is to formulate a large-scale mixed-integer linear program that captures the relevant fixed and variable operating costs for each facility and each major product family. The fixed costs are usually associated with the investment and/or overhead costs for opening and operating a facility, or with allocating a product family in a facility. The variable costs include not only the manufacturing, procurement and distributions costs, but also the tariffs and taxes that depend on the network design. The network design problem focuses on the design of two or three major echelons in the SC for multiple products. Due to the nature of the problem being solved, network design is typically solved every two to five years (Graves and Willems 2003).

With regard to the financial area, it is widely recognized that financial assets bear a strong and direct relation to core aspects of SCs, such as inventories, capacity expansion, and allocation and purchase of raw material and services. Most of SC modeling approaches account for fixed assets when the economic performance of the available alternatives is assessed in the design phase. However, in the planning formulation, they usually ignore the net working capital (NWC), which represents the variable assets associated with the daily operations. NWC is constituted by material inventories, accounts receivable (physical distribution), accounts payable (procurement), and cash. Clearly, all of these components are directly affected by decisions associated with supply chain operations. NWC can be understood as the capital tied up within the cash conversion cycle, which measures how efficiently an enterprise converts its inputs into cash through final product sales (Fig. 2.1). The less the capital is tied up by supply chain operations, the better the performance will be in terms of the business's bottom line. Note that the NWC is not a static figure, in fact, is very likely to change from period to period throughout the planning horizon, according to the SC decision tactics.

The proposed approach endeavors to model the corporate value (CV) considering each of the components that are specified in Fig. 2.2. Among these components,

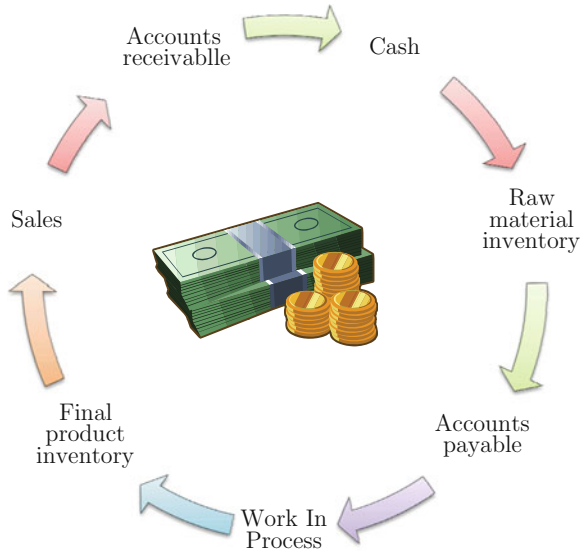


Fig. 2.1 Cash conversion cycle

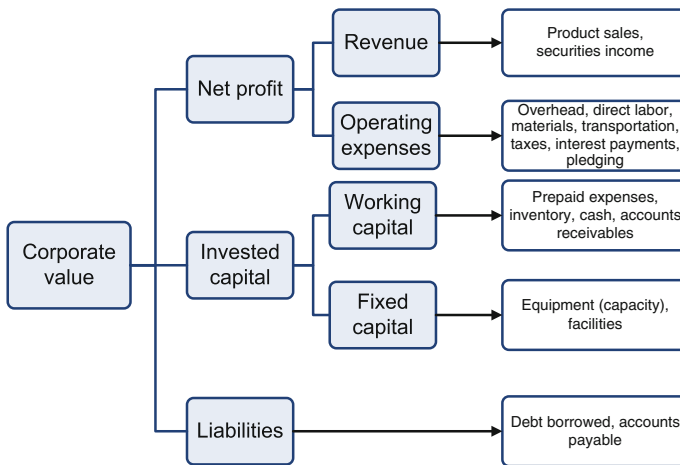


Fig. 2.2 Corporate value components

the NWC and its change is explicitly considered. Note that the CV of the firm is calculated by means of the discounted-free-cash-flow (DFCF) method and is adopted as the objective to be maximized.

The deterministic design/planning problem of a multi-echelon SC with financial considerations can be stated as follows.

The following information is given:

Process operations data

- A fixed time horizon.
- A set of products.
- A set of markets where products are available to customers and their respective demands.
- A set of potential geographical sites for locating manufacturing plants and distribution centers.
- A set of potential equipment for manufacturing the different products at the set of plants.
- Lower and upper bounds for capacity expansion of equipment and distribution centers .
- Product recipes (mass balance coefficients and consumption of capacity).
- Suppliers capacity.
- Minimum utilization rate of capacity.

Financial data

- Direct cost parameters such as production, handling, transportation, and raw material costs.
- Product prices at each market during the time horizon.
- Coefficients for investment and sales of marketable securities.
- Discount factors for prompt payment and amount purchased to suppliers.
- Relationship between capital investment and capacity of plants and distribution centers.
- Relationship between indirect expenses and equipment capacity of plants, and distribution centers.
- Pledging costs.
- Tax rate and number of depreciation time periods.
- Interest rate for the long- and short-term debt.
- Salvage value.
- Shareholders risk premium data.

The goal is to determine:

- The facilities to be opened.
- The expansion of equipment capacity at each potential plant and distribution center.
- The assignment of manufacturing and distribution tasks to the network nodes.
- The amount of final products to be sold.
- The investments and sales of marketable securities.
- The amount of accounts receivable pledged at each period.
- The schedule of payments to suppliers at each time period.
- The long and short term debt acquired and repaid at each time period.

such that the corporate value evaluated at the end of the planning horizon is maximized.

2.3 Mathematical Formulation: A Holistic Model

The mathematical formulation derived to address the problem described earlier is presented later. The model variables and constraints can be classified into four groups. The first includes the process operations constraints given by the supply chain topology. The equations that allow integrating the operations and financial models are included in the second group. The third group deals with the financial area. Finally, the equations and variables required to compute the corporate value are incorporated in the fourth group. These sets of equations are described next in detail.

2.3.1 Design–Planning Formulation

The structure of the SC that is taken as reference to develop the mathematical model is illustrated in Fig. 2.3. The design/planning mathematical formulation is based on the work of Hugo and Pistikopoulos (2005) in which the authors presented a mathematical methodology that included life cycle assessment criteria as an additional objective to be optimized at the strategic level of the SCM. The model has been enhanced to allow the storage of products, and to include distribution center nodes in the supply chain network. The model equations are described in detail in the next sections.

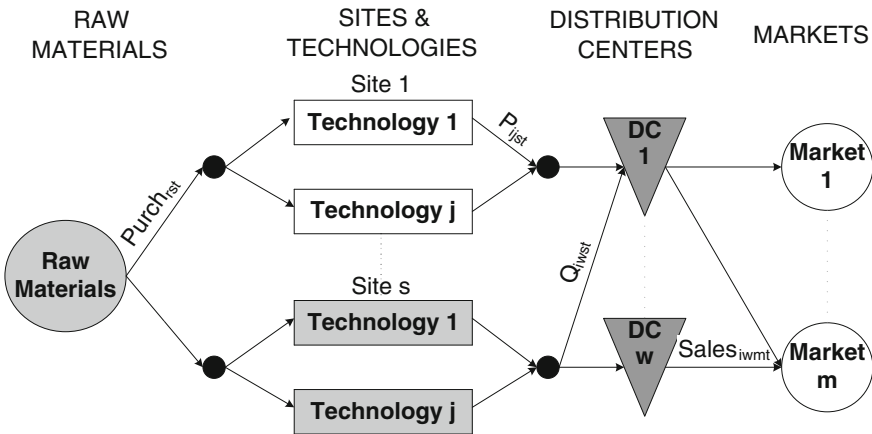


Fig. 2.3 Supply chain model structure

2.3.1.1 Material Balance Constraints

The material balance must be satisfied in each of the nodes that integrate the supply chain network.

Manufacturing Sites

Equation (2.1) represents the material balance for each raw material r consumed at each manufacturing site s in every time period t . This equation states that the purchases of raw material r provided by suppliers e (E_r) together with the initial inventory kept at the site must equal the inventory at the end of period t plus the quantity consumed by the manufacturing tasks. Note that this equation should be only applied to those products consuming raw material r and manufactured in equipment j of plant s ($i \in (I_j \cap I_r)$).

$$\sum_{e \in E_r} Purch_{erst} + SI_{rst-1} = SI_{rst} + \sum_j \sum_{i \in (I_j \cap I_r)} \alpha_{rij} P_{ijst} \quad \forall r, s, t \quad (2.1)$$

The mass balance for final products i in each manufacturing site s is enforced via Eq. (2.2). This expression states that the amount of final product manufactured at each site during a given time period t and the initial stock of the product must equal the final inventory of the product and the amount delivered from the site to the distribution centers w .

$$\sum_{j \in J_i} P_{ijst} + SO_{ist-1} = SO_{ist} + \sum_w Q_{iwt} \quad \forall i, s, t \quad (2.2)$$

Distribution Centers

Equation (2.3) states the material balance for distribution centers w . This equation makes the total amount of final product i coming from all sites s plus the initial inventory of the product kept at the distribution center must equal to the final inventory plus the sales in final markets m .

$$\sum_s Q_{iwt} + SW_{iwt-1} = SW_{iwt} + \sum_m Sales_{iwm} \quad \forall i, w, t \quad (2.3)$$

Marketplaces

This model assumes that a portion of the Demand can actually be left unsatisfied due to limited production capacity. Thus, Eq. (2.4) forces the sales of product i that take place in market m during time period t to be less than or equal to the Demand.

$$\sum_w Sales_{iwm} \leq Dem_{imt} \quad \forall i, m, t \quad (2.4)$$

The ability of responding to customer requirements turns out to be one of the most basic functions of supply chain management (Guillén-Gosálbez et al. 2005b). Therefore, customer service level (CSL) should also be taken into consideration when formulating a supply chain model (Chen et al. 2003). As proposed by Guillén-Gosálbez et al. (2005b), constraint (2.5) can be considered, which explicitly takes into account the Demand satisfaction strategy of the enterprise. This equation imposes a minimum target for the Demand satisfaction (*Min CLS*), which must be attained in all time periods t .

$$\frac{\sum_i \sum_w \sum_m Sales_{iwm}}{\sum_i \sum_m Dem_{imt}} \geq Min\ CLS \quad \forall t \quad (2.5)$$

2.3.1.2 Capacity and Facilities Location Constraints

These constraints are also inspired in the work by Hugo and Pistikopoulos (2005). Two different variables are defined, FS_{jst} and FW_{wt} , which represent the total capacity of equipment j in manufacturing sites s and distribution centers w during time period t , respectively.

Furthermore, variables FSE_{jst} and FWE_{wt} denote the capacity expansion of the different facilities of the network during time period t . The establishment of a facility takes place in the first time period in which these variables become a nonzero value. It is worth noting that the model is sufficiently general to address not only the design of a new supply chain, but also the retrofitting of an existing network. In the latter case, the problem should be formulated by fixing at time period $t = 0$ the value of the variables representing the facilities capacity according to the initial network topology.

Capacity Expansion

Equations (2.6) and (2.7) are added to control the changes in facilities capacities over time. These constraints include the binary variables V_{jst} and X_{wt} , which take a value of 1 if the facility being represented (either the equipment j at manufacturing site s or the distribution center w) is expanded in capacity and zero otherwise. Notice that the capacity increments are bounded in the range $[FSE_{jst}^L, FSE_{jst}^U]$, which represents the realistic physical interval in which they must fall.

$$V_{jst} FSE_{jst}^L \leq FSE_{jst} \leq V_{jst} FSE_{jst}^U \quad \forall j, s, t \quad (2.6)$$

$$X_{wt} FWE_{wt}^L \leq FWE_{wt} \leq X_{wt} FWE_{wt}^U \quad \forall w, t \quad (2.7)$$

Equations (2.8) and (2.9) are added to update the total capacity (FS_{jst} and FW_{wt}) by the amount increased during planning period t (FSE_{jst} and FWE_{wt}).

$$FS_{jst} = FS_{jst-1} + FSE_{jst} \quad \forall j, s, t \quad (2.8)$$

$$FW_{wt} = FW_{wt-1} + FWE_{wt} \quad \forall w, t \quad (2.9)$$

Establishing of New facilities

Equations (2.10)–(2.12) are included to determine the planning period t when a manufacturing site s initiates its operation. SB_{st} is a binary variable that takes the value of 1 if the facility is opened at period t and 0 otherwise. Equation (2.10) enforces the necessary conditions to define the new binary variable. If the binary variable that represents the capacity increment of any equipment j at site s in period t (V_{jst}) equals one, the summation of the new binary variable from the initial period to the current one must also equal one. Equation (2.12) is the reformulation of the previous logic condition and it is obtained by replacing the implication by its equivalent disjunction (see Eq. (2.11)). Equation (2.13), which is similar to constraint (2.12), is applied to enforce the definition of the binary variable SW_{wt} , which must equal 1 if the warehouse w is opened in period time t and 0 otherwise.

$$V_{jst} = 1 \Rightarrow \sum_{t'=1}^t SB_{st'} = 1 \quad \forall j, s, t \quad (2.10)$$

$$[\neg V_{jst}] \vee [\sum_{t'=1}^t SB_{st'} = 1] \quad \forall j, s, t \quad (2.11)$$

$$1 - V_{jst} + \sum_{t'=1}^t SB_{st'} \geq 1 \quad \forall j, s, t \quad (2.12)$$

$$1 - X_{wt} + \sum_{t'=1}^t SW_{wt'} \geq 1 \quad \forall w, t \quad (2.13)$$

Capacity Utilization

Equation (2.14) forces the total production in each plant to be greater than a minimum desired production ($\beta_{sj}FS_{jst-1}$) and lower than the available capacity (FS_{jst-1}). In this equation, θ_{ij} represents the capacity utilization of equipment j by product i and β_{sj} is the minimum percentage of utilization of equipment j at site s .

$$\beta_{sj}FS_{jst-1} \leq \sum_{i \in I_j} \theta_{ij}P_{ijst} \leq FS_{jst-1} \quad \forall j, s, t \quad (2.14)$$

Equation (2.15) is analogous to constraint (2.14). Here, v_i and γ_w constitute the specific volume of product i and the minimum percentage of capacity utilization of distribution center w , respectively.

$$\gamma_w FW_{wt-1} \leq \sum_i v_i SW_{iwt} \leq FW_{wt-1} \quad \forall w, t \quad (2.15)$$

Suppliers Limitations

The model assumes a maximum availability of raw materials by using Eq. (2.16). It forces the amount of raw material r purchased from supplier e at each time period t to be lower than an upper bound given by physical limitations (A_{ert}). In this expression, R_e denotes the set of raw materials provided by supplier e .

$$\sum_s Purch_{erst} \leq A_{ert} \quad \forall e, r \in R_e, t \quad (2.16)$$

2.3.2 Integration Between Models

The integration between the operational and financial formulations is carried out through the revenue, direct costs, fixed cost associated with the operation of the network, and the total capital investment.

2.3.2.1 Revenue

Revenue is calculated by means of net sales which are the income source related to the normal supply chain activities. The total revenue incurred in any period t can be easily computed from the sales of products executed in period t as it is stated in Eq. (2.17).

$$ESales_t = \sum_i \sum_w \sum_m Sales_{iwm} Price_{imt} \quad \forall t \quad (2.17)$$

Additionally, the cash collected from sales executed in any period t and maturing in period t' ($ASales_{tt'}$) can be easily computed from the sales of products executed in period t , the fraction of these sales that will be collected in period t' and the prices of the products sold, as it is stated in Eq. (2.18). Here, $\delta_{mtt'}$ denotes the fraction of sales carried out in market m in period t that will be paid in period t' .

$$ASales_{it'} = \sum_i \sum_w \sum_m Sales_{iwm} \delta_{mtt'} Price_{imt} \quad \forall t, t' > t \quad (2.18)$$

2.3.2.2 Direct Cost

The external purchases from supplier e at every period t ($EPurch_{et}$), which are computed through Eq. (2.19), include the purchases of raw materials and distribution services and production utilities.

$$EPurch_{et} = Purch_{et}^{rm} + Purch_{et}^{tr} + Purch_{et}^{prod} \quad \forall e, t \quad (2.19)$$

Raw Materials

The external raw material purchases to supplier e at every period t ($EPurch_{et}$) can be then computed through Eq. (2.20).

$$Purch_{et}^{rm} = \sum_r \sum_s Purch_{erst} \psi_{ert} \quad \forall e, t \quad (2.20)$$

Quantity Discount

Furthermore, Eqs. (2.21)–(2.23) can be added to model quantity discounts, i.e., price reductions offered by the suppliers to induce large orders. Certainly, the relationship between the discount factor offered by external supplier e for raw material r (DF_{erd}) and the amount of raw material purchased can be modeled as a piecewise linear function (see Fig. 2.4). The inclusion of these constraints allows the potential benefits

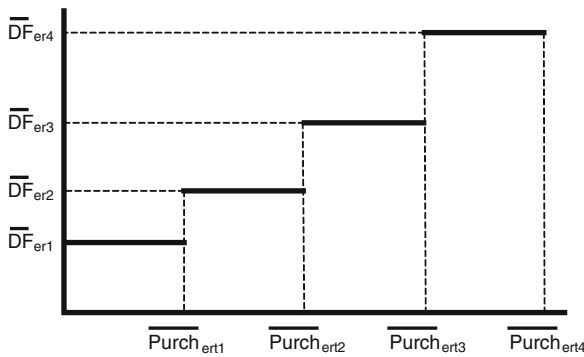


Fig. 2.4 Piecewise linear function of the discount factors

of reduced purchase prices and fewer orders to be traded off against the increase in inventory costs. Specifically, one defines a set of discounts intervals D_{er} for each raw material r for which supplier e offers quantity discounts ($r \in DR_e$). Each interval corresponds to a different discount factor DF_{erd} . The limits of interval $d \in D_{er}$ are denoted as $\overline{Purch}_{erd-1}^{rm}$ and $\overline{Purch}_{erd}^{rm}$. We introduce a new set of binary variables F_{erd} that take the value of 1 if the amount of raw material r purchased from supplier e in period t by all the sites falls into discount interval d , and 0 otherwise:

$$F_{erd} = \begin{cases} 1 & \text{if } Purch_{ert}^{rm} \in [\overline{Purch}_{erd-1}^{rm}, \overline{Purch}_{erd}^{rm}] \\ 0 & \text{otherwise} \end{cases}$$

To enforce the above definition, the following linear constraints are applied (Tsiakis et al. 2001):

$$\sum_{d \in D_{er}} F_{erd} = 1 \quad \forall e \in DR_e, r, t \quad (2.21)$$

$$F_{erd-1} \overline{Purch}_{erd-1}^{rm} \leq Purch_{erd}^{rm} \leq F_{erd} \overline{Purch}_{erd}^{rm} \quad \forall e \in DR_e, r, t, d \in D_{er} \quad (2.22)$$

$$Purch_{ert}^{rm} = \sum_{d \in D_{er}} Purch_{erd}^{rm} \quad \forall e \in DR_e, r, t \quad (2.23)$$

Constraint (2.21) forces each order to fall into a single interval, i.e., only one of the variables X_{erd} (say, for $d = d^*$) takes a value of 1, with all others being zero. Constraint (2.22) allocates each of the orders to its corresponding interval using the defined binary variable F_{erd} . Such equation forces the auxiliary continuous variable $Purch_{erd}^{rm}$ to equal 0 for all $d \neq d^*$, while also bounding $Purch_{erd^*}^{rm}$ in the range $[\overline{Purch}_{erd^*-1}^{rm}, \overline{Purch}_{erd^*}^{rm}]$. Finally, constraint (2.23) expresses the condition for which the summation of the auxiliary variable $Purch_{erd}^{rm}$ over d must equal the variable $Purch_{ert}^{rm}$. This implies that $Purch_{ert}^{rm} = Purch_{erd^*}^{rm}$ and, therefore, $Purch_{ert}^{rm} \in [\overline{Purch}_{erd^*-1}^{rm}, \overline{Purch}_{erd^*}^{rm}]$, as desired. Note that similar constraints could be easily derived to account for other types of quantity discounts, i.e., in utilities, transportation services and so forth.

Taking into account the discounts offered by the suppliers e for raw material r for a set of discount intervals d , which are denoted by DF_{erd} , the total amount of money to be invested in raw materials is the following:

$$Purch_{et}^{rm} = \sum_r \sum_{d \in D_{er}} Purch_{erd}^{rm} \psi_{ert} F_{erd} (1 - DF_{erd}) \quad \forall e \in DR_e, t \quad (2.24)$$

Distribution and Production Costs

On the other hand, “purchase” of distribution services and production utilities are determined through Eqs. (2.25) and (2.26). Here, ρ_{eiws}^{tr1} and ρ_{eiwm}^{tr2} denote the unitary distribution cost associated with sending products from plants to warehouses and from warehouses to markets, respectively. Furthermore, τ_{ijse}^{ut1} represents the unitary production cost associated with the plants, whereas τ_{rse}^{ut2} , τ_{ise}^{ut3} , and τ_{iwe}^{ut4} represent unitary inventory costs.

$$Purch_{et}^{tr} = \sum_i \sum_j \sum_s Q_{iws} \rho_{eiws}^{tr1} + \sum_i \sum_w \sum_m Sales_{iwm} \rho_{eiwm}^{tr2} \quad \forall e, t \quad (2.25)$$

$$\begin{aligned} Purch_{et}^{prod} = & \sum_i \sum_j \sum_{ijs} P_{ijst} \tau_{ijse}^{ut1} + \sum_r \sum_s SI_{rst} \tau_{rse}^{ut2} + \sum_i \sum_s SO_{ist} \tau_{ise}^{ut3} \\ & + \sum_i \sum_w SW_{iwt} \tau_{iwe}^{ut4} \quad \forall e, t \end{aligned} \quad (2.26)$$

2.3.2.3 Indirect Cost

The total fixed cost of operating a given SC structure in every time period t can be computed by means of Eq. (2.27) as the sum of the fixed costs associated with the current plant equipment j already installed in every site s ($FCFS_{jst}FS_{jst-1}$) and the sum of the fixed costs of each distribution center w ($FCFW_{wt}FW_{wt-1}$).

$$FCost_t = \sum_j \sum_s FCFS_{jst}FS_{jst-1} + \sum_w FCFW_{wt}FW_{wt-1} \quad \forall t \quad (2.27)$$

2.3.2.4 Capital Investment

The total investment in capital or fixed assets is computed through Eq. (2.28). This equation includes the investment made to expand the capacity of equipment j in manufacturing site s in period t ($Price_{jst}^{FS}FSE_{jst}$), the investment required to open a manufacturing plant, in case it is opened at period t ($I_{st}^S SB_{st}$), the investment required to support distribution center w capacity expansion ($Price_{wt}^{FW}FWE_{wt}$), and the investment required to establish a distribution center if it is opened at period t ($I_{st}^S SB_{st}$).

$$\begin{aligned}
FAsset_t = & \sum_s \left(\sum_j Price_{jst}^{FS} FSE_{jst} + I_{st}^S SB_{st} \right) \\
& + \sum_w \left(Price_{wt}^{FW} FWE_{wt} + I_{wt}^W SW_{wt} \right) \quad \forall t \quad (2.28)
\end{aligned}$$

2.3.3 Financial Formulation

In the presented approach, the cash management associated with the supply chain operation is analyzed by extending the mathematical formulation developed by Guillén-Gosálbez et al. (2006a). Such formulation is connected to the process operations variables by the equations presented in Sect. 2.3.2. As a result of the application of this integrated model, optimal supply chain design and financial decisions can be computed simultaneously. Therefore, payments to providers, short and long term borrowing, pledging decisions and the buying/selling of securities are planned in conjunction with manufacturing and distribution tasks. The financial side of the problem is then tackled through the inclusion of a set of constraints that accommodate the aforementioned economical issues. Such constraints are described below in detail.

2.3.3.1 Cash Management Model

The financial variables and constraints of the model should be determined according to specific applicable rules (e.g., depreciation), legislation (e.g., taxes), etc. This may lead to different formulations depending on the case being analyzed. To overcome this issue, a set of general equations which intend to reflect a general case have been developed. Nevertheless, the mathematical formulation can easily be extended to other particular cases.

The financial model considers the same t planning periods applied in the strategic supply chain formulation that cover the whole time horizon. This assumption allows an easy integration of both sets of constraints into a single holistic model.

The cash balance for each planning period is the following:

$$\begin{aligned}
Cash_t = & Cash_{t-1} + ECash_t + Net_t^{CLine} - \sum_e \sum_{t'=1}^t Pay_{et't} - FCost_t + Net_t^{MS} \\
& - FAsset_t + Capital_t + Net_t^{LDebt} + Other_t \quad \forall t \quad (2.29)
\end{aligned}$$

The cash at each period t ($Cash_t$) is a function of the available cash at period $t - 1$ ($Cash_{t-1}$), the exogenous cash from sales of products or, in general, from any other cash inflow ($ECash_t$), the amount borrowed or repaid to the short-term

credit line (Net_t^{CLine}), the raw materials, production and distribution service payments on accounts payable incurred in any previous or actual period t ($Pay_{ett'}$), the fixed cost ($FCost_t$), the sales and purchases of marketable securities (Net_t^{MS}), the amount invested on facilities ($FAsset_t$), the capital supported by the shareholders of the company ($Capital_t$), the amount borrowed or repaid to the long-term credit line (Net_t^{LDebt}) and finally other expected cash outflows or inflows ($Other_t$).

Pledging and Receivables

A certain proportion of accounts receivable may be pledged at the beginning of a period. Pledging is the transfer of a receivable from the previous creditor (i.e., assigner) to a new creditor (i.e., assignee). Therefore, when a firm pledges its future receivables, it receives in the same period only a part, normally 80 %, of their face value. Thus, it can be assumed that a certain proportion of the receivables outstanding at the beginning of a period is received during that period through pledge, as stated by Eq. (2.30).

$$\sum_{t''=t-\tilde{d}_M^{max}}^{t'} Pled_{tt''} \leq \sum_{t''=t-\tilde{d}_M^{max}}^{t'} ASales_{t''t} \quad \forall t, \forall t - \tilde{d}_M^{max} \leq t'' \leq t \quad (2.30)$$

In this equation the variable $Pled_{tt'}$ represents the amount pledged within period t' on accounts receivable maturing in period t , while $ASales_{t't}$ represents the accounts receivable associated with the sales of products executed in period t' and maturing in t . Here, the parameter $\tilde{d}_M^{max}$ denotes the maximum maturing period at the markets.

$$\tilde{d}_M^{max} = \max_m \{ \tilde{d}_m \} \quad (2.31)$$

Note that pledging represents a very expensive way of getting cash that will only be used when no more credit can be obtained from the bank.

Finally, the exogenous cash is computed by means of Eq. (2.32) as the difference between the amount of sales maturing in period t and executed in previous periods t' ($ASales_{t't}$) minus the amount of receivables pledged in previous periods on accounts receivable maturing in period t , plus the amount pledged in the actual period on accounts receivable maturing in future periods. In this expression, $\phi_{t't}$ represents the face value of the receivables being pledged.

$$ECash_t = \sum_{t'=t-\tilde{d}_M^{max}}^t ASales_{t't} - \sum_{t'=t-\tilde{d}_M^{max}}^{t-1} Pled_{tt'} + \sum_{t'=t+1}^{t+\tilde{d}_M^{max}} \phi_{t't} Pled_{t't} \quad \forall t \quad (2.32)$$

Payment to Suppliers

With regard to account payable, which are due to the consumption of raw materials, production and distribution services, note that the formulation assumes that the financial officer, at his/her option, may stretch or delay payments on such accounts. Discounts for prompt payment can be obtained if purchases are paid in short time and cannot be taken if the payments are stretched. Thus, Eq. (2.33) forces the payments executed in period t' on accounts payable to supplier e incurred in period t to equal the total amount due. In this expression, technical coefficients ($Coef_{ett'}$) that multiply the payments executed in periods t' on accounts payable incurred in t , are introduced in the formulation in order to take into account the terms of raw materials, production and transport credits (i.e., 2 percent-one week, net-28 days).

$$\sum_{t'=t}^{t+\hat{d}_e} Pay_{ett'} Coef_{ett'} = EPurch_{et} \quad \forall e, t \leq T - \hat{d}_e \quad (2.33)$$

The payment constraints belonging to the last periods of time are formulated as inequalities (Eq. (2.34)), as it is not reasonable to require that total accounts payable to be zero at the end of the planning period.

$$\sum_{t'=t}^{t+\hat{d}_e} Pay_{ett'} Coef_{ett'} \leq EPurch_{et} \quad \forall e, t > T - \hat{d}_e \quad (2.34)$$

Short Term Financing

A short-term financing source is represented by an open credit line with a maximum limit imposed by the bank (Eq. (2.35)). Under an agreement with the bank, loans can be obtained at the beginning of any period and are due after one year at a given interest rate (ir_t^{SD}), which depends on the specific agreement reached with bank. Equations (2.36) and (2.37) make a balance on borrowings, considering for each period the updated debt ($CLine_{t-1}$) from the previous periods, the balance between borrows and repayments (Net_t^{CLine}) and the interest of the credit line ($ir_t^{SD} CLine_{t-1}$). Moreover, the bank regularly requires a repayment greater than or equal to the interests accumulated in previous periods, as it is stated by Eq. (2.38).

$$CLine_t \leq CLine^{max} \quad \forall t \quad (2.35)$$

$$CLine_t = CLine_{t-1}(1 + ir_t^{SD}) + Borrow_t - Repay_t \quad \forall t \quad (2.36)$$

$$Net_t^{CLine} = Borrow_t - Repay_t \quad \forall t \quad (2.37)$$

$$Repay_t \geq ir_t^{SD} CLine_{t-1} \quad \forall t \quad (2.38)$$

Long-Term Financing

Equation (2.39) balances the investment with the capital supported by shareholders ($Capital_t$) and the amount borrowed to banks as long term debt ($LBorrow_t$) at each time period t .

$$FAsset_t = LBorrow_t + Capital_t \quad \forall t \quad (2.39)$$

Equations (2.40)–(2.42) reflect the payment conditions associated with the long-term debt. Note that these constraints are similar to those associated with the short-term credit line, as in practice both types of debts can be treated in a similar way. Nevertheless, in the case of long term debt, the amount repaid in each time period $LRepay_t$ usually remains unchanged along the planning horizon.

$$LDebt_t = LDebt_{t-1}(1 + ir_t^{LD}) + LBorrow_t - LRepay_t \quad \forall t \quad (2.40)$$

$$Net_t^{LDebt} = LBorrow_t - LRepay_t \quad \forall t \quad (2.41)$$

$$LRepay_t \geq ir_t^{LD} LDebt_{t-1} \quad \forall t \quad (2.42)$$

Marketable Securities

Equation (2.43) makes a balance for marketable securities. The portfolio of marketable securities held by the firm at the beginning of the first period includes several sets of securities with known face values maturing within the time horizon (S_t^{MS}). All marketable securities can be sold prior to maturity at a discount or loss for the firm, as stated by Eq. (2.43). Revenues and costs associated with the transactions in marketable securities are given by technical coefficients ($D_{tt'}^{MS}$ and $E_{tt'}^{MS}$). $Y_{t't}^{MS}$ is the cash invested at period t on securities maturing at period t' . $Z_{t't}^{MS}$ is the cash income obtained through the security sold at period t maturing at period t' .

$$\begin{aligned} Net_t^{MS} = S_t^{MS} - \sum_{t'=t+1}^T Y_{t't}^{MS} + \sum_{t'=t+1}^T Z_{t't}^{MS} + \sum_{t'=1}^{t-1} (1 + D_{tt'}^{MS}) Y_{tt'}^{MS} \\ - \sum_{t'=1}^{t-1} (1 + E_{tt'}^{MS}) Z_{tt'}^{MS} \quad \forall t \end{aligned} \quad (2.43)$$

Equation (2.44) is applied to constraint in each period t the total amount of marketable securities sold prior to maturity to be lower than the available amount (i.e., those belonging to the initial portfolio and the ones purchased in previous periods minus those sold before period t).

$$\sum_{t''=1}^{t'} Z_{t''}^{MS} (1 + E_{t''}^{MS}) \leq S_t^{MS} + \sum_{t''=1}^{t'-1} (1 + D_{t''}^{MS}) Y_{t''}^{MS} \quad \forall t, t' < t \quad (2.44)$$

Liquidity

Equation (2.45) limits the cash in each period ($Cash_t$) to be larger than a minimum value ($MinCash$). A minimum cash is usually required to handle uncertain events, like delays in customer payments, thus ensuring enterprise liquidity. The bank requires a compensating balance, normally higher than the 20% of the amount borrowed. Therefore, the minimum cash ($MinCash$) has to be higher than the compensating balance imposed by the bank.

$$Cash_t \geq MinCash \quad \forall t \quad (2.45)$$

2.3.4 Objective Function: Using a Valuation Method

While the more common objectives used are maximum profit and minimum cost, the finance community has been making financial business decisions for years by taking into account other indicators such as market to book value, liquidity ratios, leverage, capital structure ratios, return on equity, sales margin, turnover ratios and stock security ratios, among others.

Nevertheless, nowadays the maximization of the shareholder's value (SHV) seems to be the main priority of the firms and what really drives their decisions. The use of SHV as the objective to be maximized is mainly motivated by the fact that it reflects in a rather accurate way the capacity that the company has to create value. The SHV of the firm can be indeed improved by maximizing its CV. According to Weissenrieder (1998), the market value of a company is a function of four factors: (i) investment, (ii) cash flows, (iii) economic life, and (iv) capital cost. Specifically, this model applies the discounted-free-cash-flow method (DFCF) to compute the CV of a company.

2.3.4.1 The Discounted-Free-Cash-Flow Method (DFCF)

This method has recently become the most preferred approach for the valuation of companies given its capacity of properly assessing the four main factors that contribute to create the market value of a firm. In fact, the DFCF method is well entrenched in finance theory, and its use is gaining wider acceptance in industrial scenarios. The DFCF method values a project or an entire company by determining the present value of its future cash flows and discounting them taking into account the

appropriate capital cost during the time horizon for which it is defined (i.e., economic life) Grant (2003).

According to financial theory, the enterprise market value of a firm is given by the difference between the discounted stream of future cash flows during the planning horizon and the net total debt at the beginning of its life time ($NetDebt_0$), as it is stated by constraint (2.46). The initial total debt includes both, the short and the long-term debt and also the available cash (Eq. (2.47)).

$$CV = DFCF - NetDebt_0 \quad (2.46)$$

$$NetDebt_0 = CLine_0 + LDebt_0 - Cash_0 \quad (2.47)$$

In the calculation of the DFCF, one must discount the free cash flows of each period t and the salvage value (SV) at a rate equivalent to the capital cost (see Eq. (2.48)). The salvage value could be calculated as a percentage of the total investment or by any other applicable method. The capital cost reflects the time value of the money and also the risk of the investment. In fact, the capital cost can be regarded as the expected return required to attract funds to a particular investment (Pratt 2002).

$$DFCF = \sum_{t=0}^T \frac{FCF_t}{(1 + WACC_t)^t} + \frac{SV}{(1 + WACC_t)^T} \quad (2.48)$$

The Weighted Average Capital Cost (WACC)

The capital cost can be determined through the weighted average method. This method considers the total capital structure of the company, including the overall equity and the debt, as it is shown in Eq. (2.49). In this expression, λ_t denotes the proportion of equity over the total capital investment.

$$WACC_t = \lambda_t E(ROE) + ir_t(1 - \lambda_t)(1 - trate) \quad \forall t \quad (2.49)$$

To compute the expected return on equity, which is denoted by $E(ROE)$, Eq. (2.50) is applied. In this expression, $E(ROE)$ is computed as the sum of a risk free rate r^0 and a risk premium (φRe). The former term represents the rate of return of an investment free of default risk available in the market and is usually equal to the yield to maturity offered by a government security. The latter, represents the expected amount of return above the risk-free rate in exchange for a given amount of variance (Pratt 2002, Applequist et al. 2000). One of the most commonly employed methods to estimate the risk premium is the Capital Asset Pricing Model (CAPM). For more details regarding this topic the reader is referred to Sharpe (1999).

$$E(ROE) = r^0 + \varphi Re \quad (2.50)$$

Free Cash Flows

Free cash flows at every period t (FCF_t) are given by the profit after taxes, net change in investments and change in net working capital. Specifically, the free cash flows are the difference between the net operating profit after taxes (NOPAT) and the increase in capital invested. From this definition it follows that there will be value creation if the incoming value ($Profit_t (1 - \text{trate})$) is greater than the consumed value ($\Delta NWC_t + NetInvest_t$) as shown in Eq. (2.51).

$$FCF_t = Profit_t (1 - \text{trate}) - NetInvest_t - \Delta NWC_t \quad \forall t \quad (2.51)$$

Net Operating Profit

Equation (2.52) is applied to compute the profit at each period t from the incomes associated with the sales of final products ($ESales_t$), the production costs, the cost of the distribution services ($EPurch_{et}$), fixed costs ($FCost_t$) and the change in inventory (ΔInv_t).

$$Profit_t = ESales_t - \left(\sum_e EPurch_{et} + FCost_t - \Delta Inv_t \right) \quad \forall t \quad (2.52)$$

Net Investment

The net investment at each period t represents the monetary value of the fixed assets acquired in that period minus the depreciation. As mentioned before, the depreciation term should be computed according to the specific applicable rules (e.g., Straight Line, Sum-of-years Digits, Declining Balance)

$$NetInvest_t = FAsset_t - Dep_t \quad \forall t \quad (2.53)$$

Net Working Capital

The change in net working capital associated with period t (NWC_t) is computed from the change in accounts receivable, plus the change in inventory, minus the change in accounts payable, plus any other financial expenses or incomes (FEx_t), as stated by Eq. (2.54).

$$\Delta NWC_t = (\Delta ARec_t + \Delta Inv_t - \Delta APay_t + FEx_t) \quad \forall t \quad (2.54)$$

Equation (2.55) computes the accounts receivables corresponding to period t from the sales executed in the actual or any earlier period and maturing in periods beyond the

current minus the receivables pledged in previous periods, including those associated with the current period. Equation (2.56) determines the change in accounts receivable at time period t .

$$ARec_t = \sum_{t'=t-\tilde{d}_M^{max}+1}^t \sum_{t''=t+1}^{t'+\tilde{d}_M^{max}} ASales_{t't''} - \sum_{t'=t+1}^{t+\tilde{d}_M^{max}} \sum_{t''=t'-\tilde{d}_M^{max}}^t Pled_{t't''} \quad \forall t \quad (2.55)$$

$$\Delta ARec_t = ARec_t - ARec_{t-1} \quad \forall t \quad (2.56)$$

Equation (2.57) expresses changes in inventory including raw material stocks in manufacturing sites, as well as final product stocks in distribution centers and manufacturing sites. Iu_{it}^{RM} and Iu_{it}^{FP} represent the inventory values for each raw material r and product i at each planning period t , respectively.

$$\begin{aligned} \Delta Inv_t = & \sum_i Iu_{it}^{FP} \left[\sum_s (SO_{ist} - SO_{ist-1}) + \sum_w (SW_{iwt} - SW_{iwt-1}) \right] \\ & + \sum_r \sum_s Iu_{rt}^{RM} (SI_{rst} - SI_{rst-1}) \quad \forall t \end{aligned} \quad (2.57)$$

The accounts payable ($APay_t$) are determined as the difference between all the purchases executed in previous periods ($EPurch_{et'}$) minus all payments done until the current period ($Pay_{et't'}$), as stated in Eq. (2.58). This constraint takes also into account the discounts for prompt payments ($Coef_{ett'}$). The change in accounts payable at time period t is thus represented by constraint (2.59).

$$APay_t = \sum_e \sum_{t'=1}^t EPurch_{et'} - \sum_e \sum_{t''=1}^t \sum_{t'=t''}^t Coef_{ett'} Pay_{et't'} \quad \forall t \quad (2.58)$$

$$\Delta APay_t = APay_t - APay_{t-1} \quad \forall t \quad (2.59)$$

Finally, Eq. (2.60) computes other financial expenses and incomes (FEx_t) associated with the supply chain operation at every time period t . This term includes pledging costs ($(1 - \phi_{t'})Pled_{t't}$), discounts for prompt payments to suppliers ($Pay_{et't} (Coef_{et't} - 1)$) and also the earnings ($D_{tt'}^{MS} Y_{tt'}^{MS}$) and expenses ($E_{tt'}^{MS} Z_{tt'}^{MS}$) associated with the transactions of marketable securities.

$$\begin{aligned} FEx_t = & \sum_{t'=t+1}^{t+\tilde{d}_M^{max}} (1 - \phi_{t'}) Pled_{t't} - \sum_e \sum_{t'=1}^t Pay_{et't} (Coef_{et't} - 1) \\ & + \sum_{t'} E_{tt'}^{MS} Z_{tt'}^{MS} - \sum_{t'} D_{tt'}^{MS} Y_{tt'}^{MS} \quad \forall t \end{aligned} \quad (2.60)$$

The overall problem can therefore be mathematically posed as follows:

$$\begin{aligned}
 & \text{Maximize } CV \\
 & \quad \mathcal{X}, \mathcal{Y} \\
 & \text{subject to} \\
 & \text{Eqs. (2.1)–(2.60)} \\
 & \mathcal{X} \in \{0, 1\}; \mathcal{Y} \in \mathbb{R}
 \end{aligned}$$

Here, $\mathcal{X}$ denotes the model binary variables set, while $\mathcal{Y}$ represents the model continuous variable set.

2.4 Motivating Example

The capabilities of the proposed integrated approach are illustrated by solving a retrofitting problem of a supply chain comprising several manufacturing sites, distribution centers, and markets located in different European countries. A set of potential technologies are assumed to be available in the manufacturing sites. Furthermore, several potential locations for the manufacturing sites and the distribution centers, from which the products should be transported to the final markets, are also considered, as is depicted in Fig. 2.5. The potential locations for the plants embedded

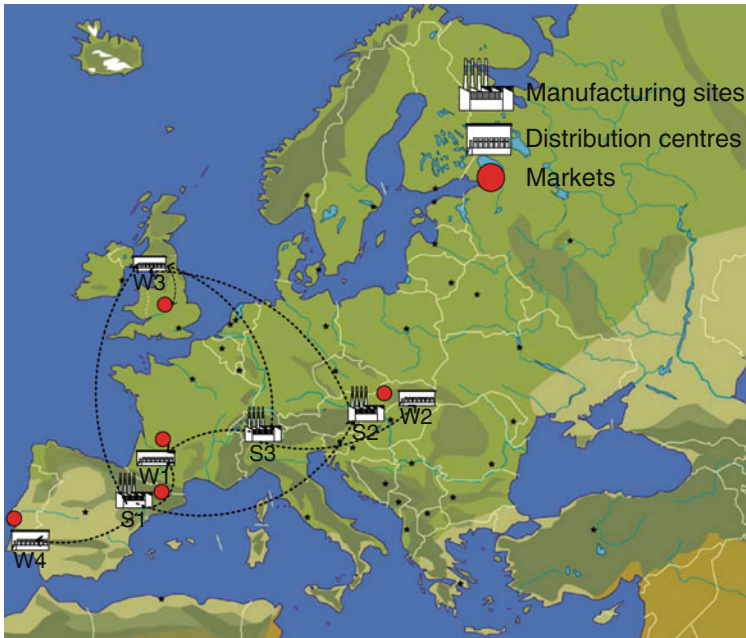


Fig. 2.5 Supply chain structure of case study

in the SC ($S1$, $S2$ and $S3$) are Barcelona (B), Budapest(Bu), and Milan (Mi). These plants can manufacture three different products ($P1$, $P2$ and $P3$) with four different technologies (TA to TD). These final products must be transported to the distribution centers prior to being sent to the final markets ($M1$ to $M5$), where they become available to customers. It is assumed an existing installed capacity of TA in $S1$ and $S3$ of 10×10^3 c.u. and 50×10^3 c.u., respectively. The investment cost associated with the establishment of a manufacturing site is equal to 8.8×10^6 m.u. The potential locations for the distribution centers ($W1$ to $W4$) are B, Bu, Manchester (M) and Lisbon (Li), whereas for the final markets are B, Bu, London (L), Li, and Toulouse (T). It is also assumed that at time zero $W1$ has an installed capacity of 4×10^3 m³. The investment needed to open a distribution center is equal to 2.5×10^6 m.u.

The initial inventories are supposed to be equal to zero for all products and raw materials. The upper bound imposed to the capacity increment of technologies at each manufacturing site is equal to 0.5×10^6 c.u. and the lower bound is 50×10^3 c.u. The lower and upper bounds imposed to the capacity expansion of distribution centers are 2×10^3 and 30×10^3 m³, respectively. The capacities of the facilities can only be increased every two years. The salvage value is considered negligible at the end of the planning horizon. The availability of utilities is assumed to be unlimited.

With regard to financial matters, it is assumed that the firm has at the beginning of the planning horizon an initial portfolio of marketable securities. Specifically, the firm owns 15×10^3 m.u. in marketable securities maturing in period 2 and 18×10^3 m.u. maturing in period 3. The initial cash is assumed to be equal to the minimum allowed cash, which is 125×10^3 m.u. Under an agreement with a bank, the firm has an open line of short-term credit at a 15 % annual interest with a maximum allowed debt of 4×10^6 m.u. The initial debt is assumed to be equal to zero and the value of the materials kept as inventories at the end of the time horizon are assumed to be a 85 % of their market prices for final products and 100 % of their cost for raw materials.

The supply chain under study has three external suppliers, the first one provides raw materials, the second one transportation services and the third one labour. Liabilities incurred with the raw materials supplier must be repaid within one month according to the terms of the credit (2 percent-same period, net-28 days for the raw materials supplier). The supplier of raw materials offers discounts for large orders. A 3 % discount is applied for orders of raw material $R1$ greater than 45×10^3 kg, and a 5 % for orders above 80×10^3 kg. The payments associated with the distribution services and labor tasks cannot be stretched and must be fulfilled within the same time period in which the purchase incidence takes place. The technical coefficients associated with the set of marketable securities that the firm has agreed to purchase and sale have been computed by considering a 2.8 % annual interest for purchases and a 3.5 % for sales. It is considered outflows of cash equal to 5.0, 7.5 and 10.0 millions m.u. in the periods 13, 15 and 17 due to wages, rents, and dividends. It is also assumed that the ratio between the long-term debt and the equity must always be kept equal to 0.41. With regard to the long-term debt, it should be noticed that the firm can access a long term credit at a 10 % annual interest. Shareholders expect an annual ROE of 30 %. The taxes rate is 30 %. Depreciation is calculated by means

of the straight line method applied over a time horizon of ten years. The rest of this case study data is found in Appendix B.

Sixty-one monthly planning periods are considered. The implementation in GAMS Brooke et al. (1998) of the integrated formulation leads to a MILP model with 40,306 equations, 46,916 continuous variables, and 252 discrete variables. It takes 185 CPU seconds to reach a solution with a 0% integrality gap on a AMD Athlon 3000 computer using the solver CPLEX (version 10.0) for the MIP problem. The integrated model is firstly solved by maximizing the CV of the firm. To explicitly show the trade-off between the CV and the standard KPIs that neglect financial considerations (i.e., NPV and profit) a two-objective optimization is applied (see Appendix A.5), taking into account in each case the above commented objectives, CV and NPV and CV and profit, respectively, at the same time. The objective of this analysis is to further explore the compromises between an integrated holistic solution and a sequential one. The NPV and the profit are computed by applying Eqs. (2.62) and (2.63), respectively.

$$FF_t = (Profit_t - FAsset_t) \quad (2.61)$$

$$TProfit = \sum_t FF_t \quad (2.62)$$

$$NPV = \sum_{t=1}^T \frac{FF_t}{(1 + RR)^t} \quad (2.63)$$

The optimal network configurations are summarized in Tables 2.2, 2.3 and 2.4. The Pareto curves obtained by applying the ϵ -constraint method are shown in Fig. 2.6. Numerical results show that the solutions computed by maximizing profit or NPV as single objectives are far away from the optimal solution using the corporate value as objective. The maximum CV solution is almost 300 % higher than the one computed by maximizing profit and 267 % higher than the one accomplished when maximizing NPV. On the other hand, the maximum profit and NPV solutions are quite similar. Moreover, from these results, it is clear that in both cases a conflict exists between the different objectives (i.e., maximum corporate value and maximum profit or NPV). Numerical results show that an improvement in profit or NPV is only possible if the decision-maker is willing to compromise the firm's CV. Certainly, SC configurations with better profits or NPVs can only be achieved at the expense of a reduction in the firm's CV.

It is worth to mention that this case study represents a very specific situation where there is one market ($M2$) in which the product prices are slightly higher in comparison with the others (1.87 %). At such market, accounts receivable are due within a large time period. Under this assumption, the design-planning model that accounts for the maximization of a biased KPI (either profit or NPV) that neglects the financial side of the problem decides to configure a supply chain network capable of easily fulfilling the Demand of market $M2$ as much as possible (see Fig. 2.7). The

Table 2.2 Maximum profit network design

Total profit		121,653,714.87 m.u.			
Net present value (NPV)		47,476,865.35 m.u.			
Corporate value (CV)		36,392,463.16 m.u.			
		Time period (t)			
		0	1	24	48
<i>Manufacturing sites</i>					
s	j	Capacity increment (c.u.)			
S1	TA	10,000.0	0.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	0.0	0.0	0.0
	TD	0.0	0.0	0.0	0.0
S2	TA	0.0	500,000.0	0.0	0.0
	TB	0.0	407,796.6	0.0	0.0
	TC	0.0	500,000.0	0.0	0.0
	TD	0.0	500,000.0	0.0	0.0
S3	TA	50,000.0	0.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	496,610.2	0.0	0.0
	TD	0.0	478,813.6	0.0	0.0
<i>Distribution centres</i>					
w	Capacity increment (m ³)				
W1	4,000.0	0.0	0.0	0.0	
W2	0.0	2,000.0	0.0	0.0	
W3	0.0	0.0	0.0	0.0	
W4	0.0	0.0	0.0	0.0	

profit and the NPV are indeed blind KPIs in the sense that they are not capable of properly assessing the financial cost associated with net working capital. As a result, accounts receivables increase in certain periods of time in which the firm has to face important payments. The cash management model is then forced to pledge them, mainly during month 18–36 (quarters 6–12). Pledging is indeed a very expensive way of getting cash and because of that the firm reduces its capacity of creating value when applying it.

On the other hand, the integrated approach that accounts for the maximization of a suitable financial objective function (i.e., corporate value) is able to properly assess the trade off between the increment in profit that can be achieved by fulfilling Demand at market $M2$ and the increment in net working capital that is required to carry out this decision. Hence, the integrated approach computes a configuration that does not fulfill the Demand in $M2$ due to the poor payment conditions associated with its customers. Consequently, the net working capital needed is reduced

Table 2.3 Maximum net present value network design

	Total profit	121,464,749.10 m.u.			
	Net present value (NPV)	47,623,655.11 m.u.			
	Corporate value (CV)	39,557,152.26 m.u.			
		Time period (<i>t</i>)			
		0	1	24	48
<i>Manufacturing sites</i>					
<i>s</i>	<i>j</i>	Capacity increment (c.u.)			
S1	TA	10,000.0	0.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	0.0	0.0	0.0
	TD	0.0	0.0	0.0	0.0
S2	TA	0.0	500,000.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	500,000.0	0.0	0.0
	TD	0.0	500,000.0	0.0	0.0
S3	TA	50,000.0	329,830.5	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	496,610.2	0.0	0.0
	TD	0.0	478,813.6	0.0	0.0
<i>Distribution centres</i>					
<i>w</i>		Capacity increment (m ³)			
W1		4,000.0	0.0	0.0	0.0
W2		0.0	2,000.0	0.0	0.0
W3		0.0	0.0	0.0	0.0
W4		0.0	0.0	0.0	0.0

significantly thus increasing the value accumulated during the whole planning horizon. This can be seen in Tables 2.5, 2.6 and 2.7, which depict the behavior of the corporate value and the structure of the consumed value during the planning horizon for each optimum SC network configuration. For the purpose of facilitating their interpretation, the planning periods (months) have been aggregated into quarters in these tables. In Fig. 2.8, financial Gantt charts for each optimal SC configuration are shown. They describe how the cash is composed and utilized during the first 25 planning periods.

To Demonstrate the advantages of using CV and its robustness to assess strategic decisions under different scenarios, the previous case study has been modified and solved. Two modifications have been done: (i) prices paid by market *M2* are equal to those of the other markets and (ii) the due time of account receivables in market *M2* has the same conditions as that offered by market *M4*. The optimal SC network configurations obtained are quite similar to those resulting in the previous

Table 2.4 Maximum corporate value network design

	Total profit	105,955,397.81 m.u.			
	Net present value (NPV)	42,068,183.09 m.u.			
	Corporate value (CV)	145,023,155.58 m.u.			
		Time period (t)			
		0	1	24	48
<i>Manufacturing sites</i>					
s	j	Capacity increment (c.u.)			
S1	TA	10,000.0	500,000.0	0.0	0.0
	TB	0.0	395,796.6	0.0	0.0
	TC	0.0	500,000.0	0.0	0.0
	TD	0.0	500,000.0	0.0	0.0
S2	TA	0.0	0.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	0.0	0.0	0.0
	TD	0.0	0.0	0.0	0.0
S3	TA	50,000.0	0.0	0.0	0.0
	TB	0.0	0.0	0.0	0.0
	TC	0.0	496,610.2	0.0	0.0
	TD	0.0	478,813.6	0.0	0.0
<i>Distribution centres</i>					
w	Capacity increment (m ³)				
W1	4,000.0	0.0	0.0	0.0	
W2	0.0	2,000.0	0.0	0.0	
W3	0.0	0.0	0.0	0.0	
W4	0.0	0.0	0.0	0.0	

case study. In Table 2.8, the values of each KPI are shown for each optimal configuration. Even for this second case, it can be observed that the maximum CV solution is 62 % better than the one computed by maximizing profit and 32 % superior than the one suggested when maximizing NPV. It is clear from these two examples that the integrated model introduced in this chapter has a great potential when addressing the challenge of designing a SC capable to preserve and improve the firms' value.

2.5 Final Considerations

This chapter has addressed the design and retrofit of supply chains taking into account financial concerns. The proposed framework applies mixed integer modeling techniques to develop holistic mathematical models that are able to optimize the strategic operations decisions in conjunction with those of finances.

Fig. 2.6 Corporate value–profit Pareto curve. **a** Corporate value versus profit. **b** Corporate value versus NPV. **c** NPV versus profit

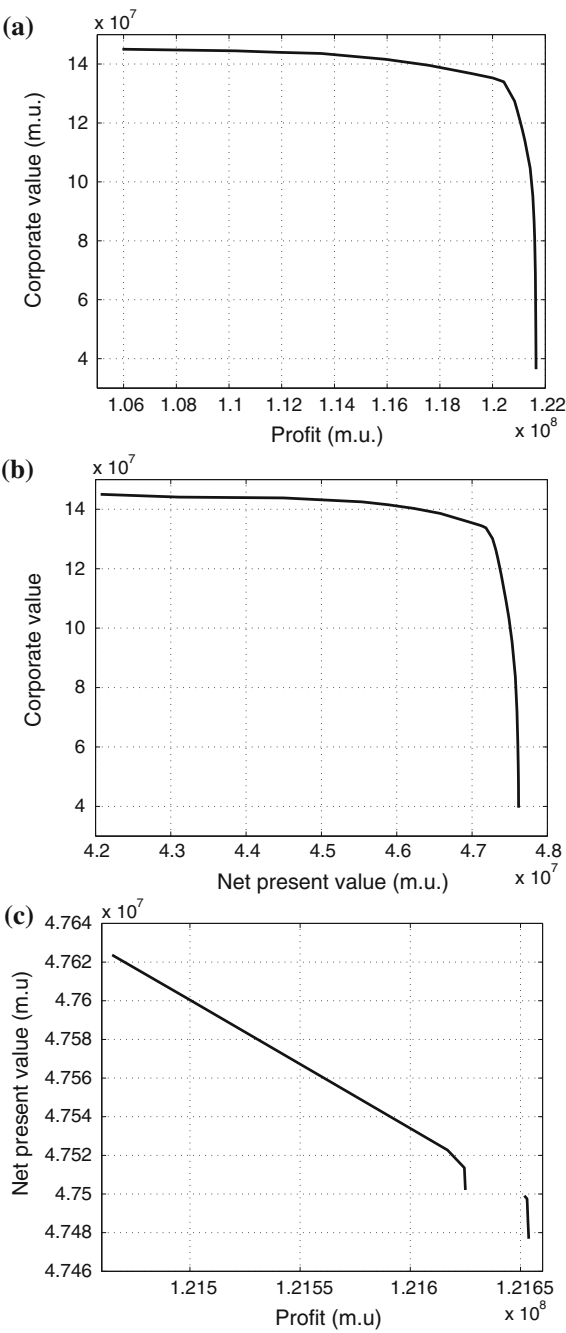
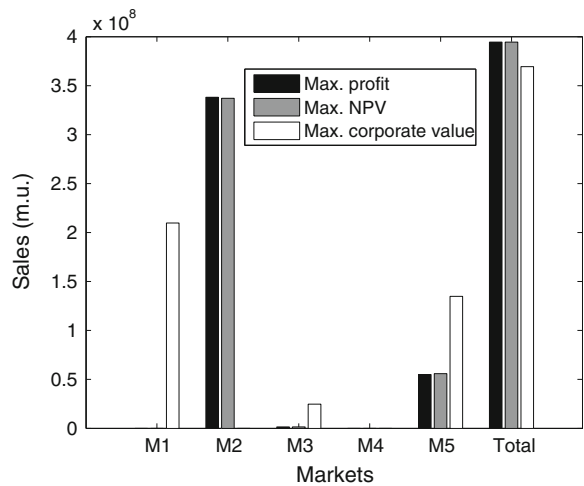


Fig. 2.7 Sales carried out in each market for each optimal SC network configuration



The main advantages of this approach have been highlighted through a case study, in which the integrated model has been compared with the traditional method. The proposed approach pursues the maximization of a suitable financial key performance indicator that is able to properly assess the expenses associated with the shortages of cash and the penalty associated with changes in net working capital (i.e., the corporate value of the firm at the end of the time horizon). Instead, the conventional strategy accounts for the maximization of a biased key performance indicator that is unable to assess the costs of financing fixed and variable assets. Numerical results show that the integrated solution not only ensures the feasibility of the strategic decisions from the financial viewpoint but also leads to a superior economic performance given its higher capacity of creating value for the firm.

The framework suggested in this book is thus in consonance with the new trends in PSE, which are going toward an enterprise wide optimization framework that aims to integrate all the functional decisions into a global model that should optimize an overall key performance measure. Here, it is proposed the corporate value measured through the discounted free cash flow method as a suitable first approach to this posed requirement.

It is worth emphasizing that it is not enough to have a static planning model reviewed only in certain periods. It will be necessary to maintain continuously updated an enterprise modeling system. This modeling system must include the financial management of capital investments at the strategic level. The bottom level must incorporate a realistic cash flow management including net working capital analysis and also short term budget. The maximum corporate value as target and the holistic model itself constitute a significant advancement in creating this ongoing planning system. To the best of our knowledge, a system based on an integrated

Table 2.5 Value accumulation at each quarter for maximum profit SC network structure (1×10^6 m.u.)

Quarter	Profit after sales	Δ Accounts receivable	Δ Accounts payable	Net investment	Other expenses	Change in invested capital	Discounted free cash flows
0	0.000	0.000	0.000	-30.351	0.000	-30.351	-30.351
1	4.979	-13.727	3.473	0.759	-1.031	-10.526	-5.400
2	5.252	-7.203	0.010	0.759	-0.575	-7.009	-1.642
3	5.235	-7.177	0.026	0.759	-0.557	-6.950	-1.539
4	5.244	-2.188	0.028	0.759	-0.526	-1.927	2.810
5	5.146	1.081	-0.016	0.759	-0.811	1.013	5.110
6	5.381	5.931	0.046	0.759	-4.053	2.684	6.507
7	5.331	2.857	-0.092	0.759	-10.469	-6.945	-1.231
8	5.379	2.157	-0.019	0.759	-9.875	-6.978	-1.169
9	5.376	1.554	0.017	0.759	-9.267	-6.937	-1.097
10	5.375	-1.939	-0.020	0.759	-5.699	-6.900	-1.029
11	5.334	0.267	0.070	0.759	-7.901	-6.805	-0.953
12	5.401	-0.988	-0.080	0.759	-6.558	-6.867	-0.911
13	5.378	2.972	0.027	0.759	-10.554	-6.797	-0.847
14	5.385	-5.259	0.021	0.759	-2.293	-6.772	-0.795
15	5.354	0.034	-0.003	0.759	-7.484	-6.693	-0.737
16	5.397	-6.640	0.000	0.759	-0.836	-6.717	-0.698
17	5.365	-2.724	0.058	0.759	-4.729	-6.637	-0.645
18	5.417	-6.582	-0.079	0.759	-0.290	-6.193	-0.381
19	5.337	16.801	-3.465	0.759	-0.068	14.027	9.058
20	5.338	20.772	3.462	0.759	0.069	25.062	13.619

Table 2.6 Value accumulation at each quarter for maximum NPV SC network structure (1×10^6 m.u.)

Quarter	Profit after sales	Δ Accounts receivable	Δ Accounts payable	Net investment	Other expenses	Change in invested capital	Discounted free cash flows
0	0.000	0.000	0.000	-29.832	0.000	-29.832	-29.832
1	4.954	-13.684	3.473	0.746	-1.035	-10.500	-5.400
2	5.226	-7.171	0.010	0.746	-0.567	-6.983	-1.642
3	5.210	-7.148	0.026	0.746	-0.550	-6.927	-1.540
4	5.214	-2.151	0.028	0.746	-0.520	-1.897	2.809
5	5.107	1.231	-0.016	0.746	-0.769	1.192	5.226
6	5.357	5.393	0.046	0.746	-3.617	2.568	6.395
7	5.307	3.162	-0.092	0.746	-10.742	-6.926	-1.234
8	5.356	-1.238	-0.019	0.746	-6.447	-6.959	-1.173
9	5.352	-3.654	0.017	0.746	-4.027	-6.919	-1.100
10	5.351	5.696	-0.020	0.746	-13.304	-6.882	-1.033
11	5.310	-6.120	0.070	0.746	-1.483	-6.788	-0.957
12	5.378	-6.572	-0.080	0.746	-0.944	-6.851	-0.916
13	5.354	-4.029	0.027	0.746	-0.364	-3.621	1.016
14	5.362	-0.452	-3.469	0.746	-0.019	-3.194	1.230
15	5.331	0.240	0.000	0.746	0.070	1.056	3.515
16	5.373	-0.027	0.000	0.746	0.107	0.825	3.271
17	5.342	-0.850	0.000	0.746	0.145	0.041	2.733
18	5.393	-0.196	0.000	0.746	0.179	0.729	2.979
19	5.313	16.801	0.000	0.746	0.218	17.765	10.781
20	5.314	20.772	3.462	0.746	0.175	25.156	13.650

Table 2.7 Value accumulation at each quarter for maximum corporate value SC network structure (1×10^6 m.u.)

Quarter	Profit after sales	Δ Accounts receivable	Δ Accounts payable	Net investment	Other expenses	Change in invested capital	Discounted free cash flows
0	0.000	0.000	0.000	-30.344	0.000	-30.344	-30.344
1	5.011	-13.996	3.473	0.759	-0.805	-10.570	-5.409
2	5.113	-1.556	-1.524	0.759	-0.490	-2.811	2.149
3	5.047	0.000	-1.949	0.759	-0.158	-1.349	3.294
4	5.016	0.000	0.000	0.759	-0.122	0.637	4.869
5	5.029	0.000	0.000	0.759	-0.105	0.653	4.699
6	5.034	0.000	0.000	0.759	-0.116	0.643	4.514
7	5.005	0.000	0.000	0.759	-0.071	0.687	4.338
8	5.060	0.000	0.000	0.759	-0.036	0.723	4.231
9	5.049	0.000	0.000	0.759	0.002	0.760	4.081
10	5.054	0.000	0.000	0.759	0.039	0.797	3.946
11	5.011	0.000	0.000	0.759	0.077	0.835	3.786
12	5.084	0.000	0.000	0.759	0.111	0.869	3.701
13	5.047	0.000	0.000	0.759	0.149	0.908	3.554
14	5.065	0.000	0.000	0.759	0.186	0.944	3.444
15	5.031	0.000	0.000	0.759	0.224	0.982	3.308
16	5.068	0.000	0.000	0.759	0.260	1.019	3.215
17	5.046	0.000	0.000	0.759	0.298	1.057	3.095
18	5.095	0.000	0.000	0.759	0.334	1.092	3.012
19	5.026	0.000	0.000	0.759	0.373	1.131	2.878
20	1.386	15.552	3.462	0.759	0.172	19.945	9.554

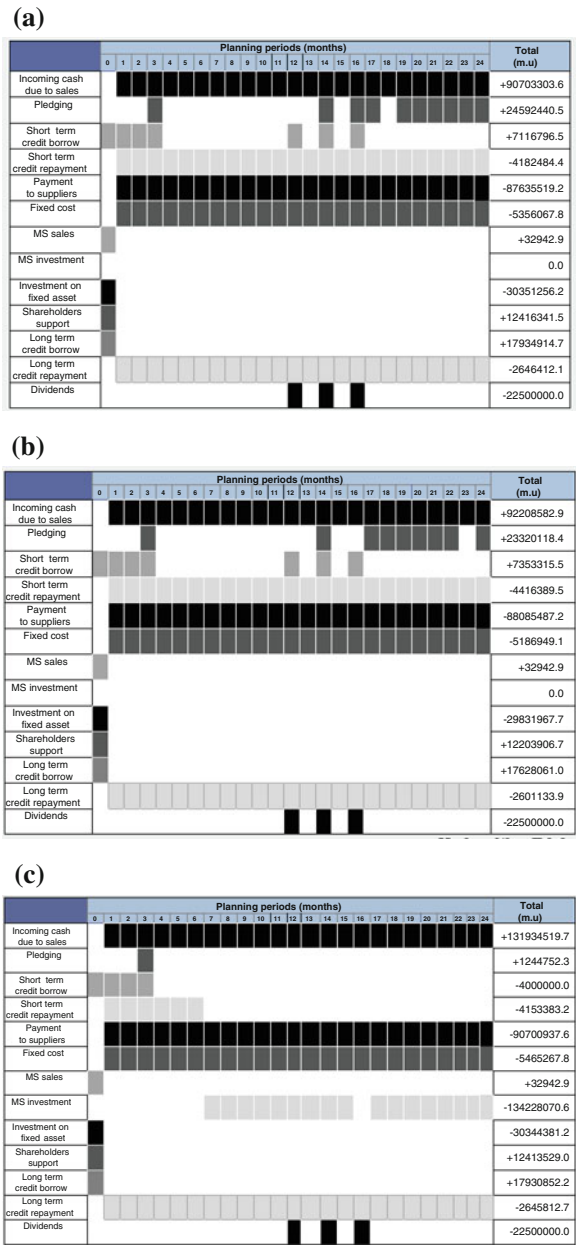


Fig. 2.8 Financial Gantt charts. a Optimal profit. b Optimal NPV. c Optimal CV

Table 2.8 KPI values of optimal SC network configurations for second case study (m.u.)

Network configuration	KPI		
	Total profit	NPV	CV
Optimal total profit	116,597,744.59	45,374,556.23	89,386,052.53
Optimal NPV	116,377,423.52	45,516,838.30	110,018,635.40
Optimal CV	105,955,397.81	42,068,183.09	145,023,155.58

model that takes into account a detailed financial analysis had not been implemented so far. Next chapters will discuss additional extensions of the concept of integration to the benefit of supply chain management.

2.6 Notation

Indices

- e Suppliers
- d Discount interval
- i Products
- j Plant equipment
- m Markets
- r Raw materials
- s Manufacturing sites
- t Planning periods
- w Distribution centers

Sets

- D_{er} Discounts intervals for each raw material r for which supplier e offers quantity discount
- DR_e Raw materials for which supplier e offers quantity discounts
- E_r Set of suppliers e that provide raw material r
- I_j Products that can be processed in plant equipment j
- I_r Products that consumed raw material r
- J_i Equipment that can process product i
- Re Set of raw materials provided by supplier e
- τ Planning periods in which investments on facilities are allowed

Parameters

A_{ert}	Maximum availability of raw material r in period t associated with supplier e
$CLine^{max}$	Upper bound of short term credit line
$Coef_{ett'}$	Technical discount coefficient for payments to external supplier e executed in period t' on accounts incurred in period t
$\hat{d}_e$	Maximum delay on payments of supplier e
$\tilde{d}_m$	Maximum delay in receivables at market m
$\tilde{d}^{max}$	Maximum delay in receivables at all markets
$D_{tt'}^{MS}$	Technical coefficient for investments in marketable securities
DF_{erd}	Discount factor associated with discount interval d for raw material r offered by external supplier e
Dem_{imt}	DemDemand of product i at market m in period t
$disc_{erd}$	Discount offered by supplier e for raw material r at interval d
$E_{tt'}^{MS}$	Technical coefficient for sales of marketable securities
$E(ROE)$	Expected return on equity
$FCFS_{jst}$	Fixed cost per unit of capacity of plant equipment j at site s in period t
$FCFW_{wt}$	Fixed cost per unit of capacity of distribution center w in period t
g_{ert}	Cost of raw material r provided by supplier e in period t
ir_t^{LD}	Interest rate of long term debt
ir_t^{SD}	Interest rate of short term debt
I_{st}^S	Investment required to open site s in period t
I_{wt}^W	Investment required to open distribution center w in period t
Iu_{rt}^{RM}	Value of inventory of raw material r in period t
Iu_{it}^{EP}	Value of inventory of product i in period t
$MinCash$	Lower bound of cash
$MinCSL$	Lower bound of customer service level
$Other_t$	Other expected outflows or inflows of cash in period t
$NetDebt_0$	Net total debt at initial period
$Price_{imt}$	Price of product i at market m in period t
$Price_{jst}^{FS}$	Investment required per unit of capacity of equipment j increased at site s in period t
$Price_{wt}^{FW}$	Investment required per unit of capacity of distribution center w increased in period t
rf	Risk free rate of return
rp	Risk premium rate
RR	Return rate
S_t^{MS}	Marketable securities of the initial portfolio maturing in period t
$trate$	Tax rate
T	Length of planning horizon

Binary Variables

F_{ertd}	1 if the amount of raw material r purchased from supplier e in period t is within discount interval d , 0 otherwise
SB_{st}	1 if site s is opened in period t , 0 otherwise
V_{jst}	1 if the capacity of equipment j is increased at site s in period t , 0 otherwise
WB_{wt}	1 if distribution center w is opened in period t , 0 otherwise
X_{wt}	1 if the capacity of distribution center w is increased in period t , 0 otherwise

Continuous Variables

$APay_t$	Amount of accounts payable in period t
$ARec_t$	Amount of accounts receivable in period t
$ASales_{tt'}$	Sales executed in period t and receivable in period t'
$Borrow_t$	Total amount borrowed from the short term credit line in period t
$Capital_t$	Capital supported by shareholders in period t
$Cash_t$	Cash in period t
$CLine_t$	Short-term debt in period t
CSL	Customer service level calculated at the end of the planning horizon
CV	Corporate value at the end of the planning horizon
Dep_t	Depreciation in period t
$DFCF$	Sum of discounted free cash flows at the end of the planning horizon
$ECash_t$	Exogenous cash in period t
$EPurch_{et}$	Economic value of purchases executed in period t to supplier e
$ESales_t$	Economic value of sales carried out in period t
$FAsset_t$	Increment in fixed assets in period t
FCF_t	Free cash flows in period t
$FCost_t$	Fixed cost in period t
FEx_t	Other financial expenses and incomes in period t
FF_t	Funds flow in period t
FS_{jst}	Total capacity of plant equipment j during period t at site s
FSE_{jst}	Capacity increment of plant equipment j during period t at site s
FW_{jst}	Total capacity at distribution center w during period t
FWE_{jst}	Capacity increment at distribution center w during period t
$LBorrow_t$	Total amount of money borrowed from the long-term credit line in period t
$LDebt_t$	Long term debt in period t
$LRepay_t$	Total amount repaid to the long-term credit line in period t
Net_t^{CLine}	Total amount of money borrowed or repaid to the short term credit line in period t
Net_t^{LDebt}	Total amount of money borrowed or repaid to the long-term credit line in period t
Net_t^{MS}	Total amount received or paid in securities transactions in period t
$NetInvest_t$	Net investment in period t
NPV	Net present value computed for whole planning horizon
P_{ijst}	Production rate of product i in equipment j at site s in period t

$Pay_{it'}$	Payments to external supplier e executed in period t' on accounts payable incurred in period t
$Pled_{it'}$	Amount pledged within period t' on accounts receivable maturing in period t
$Profit_t$	Profit achieved in period t
$Purch_{et}^{rm}$	Amount of money payable to supplier e in period t associated with consumption of raw materials
$Purch_{et}^{tr}$	Amount of money payable to supplier e in period t associated with consumption of transport services
$Purch_{et}^{pr}$	Amount of money payable to supplier e in period t associated with consumption of production utilities
$Purch_{erst}$	Amount of raw material r purchased to supplier e at site s in period t
$Purch_{et}^{rm}$	Amount of raw material r purchased in period t
$q_{end t}$	Amount of material r within discount interval d purchased to supplier e in period t
Q_{iwt}	Amount of product i sent from site s to distribution center w in period t
$Repay_t$	Total amount repaid to the short-term credit line in period t
$Sales_{iwm t}$	Amount of product i sold from distribution center w in market m in period t
SI_{rst}	Amount of stock of raw material r at site s in period t
SO_{ist}	Amount of stock of product i at site s in period t
SV	Salvage value of facilities at the end of planning horizon
SW_{iwt}	Amount of stock of product i at distribution center w in period t
$TProfit$	Total profit achieved at end of planning horizon
$WACC_t$	Weighted average cost of capital in period t
$Y_{it'}^{MS}$	Cash invested in period t' in marketable securities maturing in period t
$Z_{it'}^{MS}$	Security sold in period t' maturing in period t
$\Delta APay_t$	Change in amount of accounts payable in period t
$\Delta ARec_t$	Change in amount of accounts receivable in period t
ΔInv_t	Change in inventory value in period t
ΔNWC_t	Change in net working capital in period t

Greek Symbols

α_{rij}	Fixed coefficient for consumption of raw material r by product i
β_{sj}	Minimum utilization of plant equipment j capacity allowed at site s
γ_w	Minimum utilization of distribution center w capacity allowed
$\delta_{mtt'}$	Fraction of sales carried out in period t that are receivable in period t' in market m
θ_{ij}	Capacity utilization of plant equipment j by product i
λ_t	Proportion of equity over total capital investment in period t
ρ_{eiws}^{tr1}	Unitary transport costs of product i from plant s to warehouse w payable to external supplier e
ρ_{eiwm}^{tr2}	Unitary transport costs of product i from warehouse w to market m

τ_{ijse}^{ut1}	Cost associated with product i manufactured with equipment j in site s and payable to external supplier e
τ_{rse}^{ut2}	Cost associated with handling the inventory of raw material r in site s and payable to external supplier e
τ_{ise}^{ut3}	Cost associated with handling the inventory of final product i in site s and payable to external supplier e
τ_{iwe}^{ut3}	Cost associated with handling the inventory of final product i in warehouse w and payable to external supplier e
v_i	Specific volume of product i
$\phi_{tt'}$	Face value of accounts maturing in period t pledged in period t'
ψ_{ert}	Price of raw material r offered by external supplier e in time period t

Superscripts

L	Lower bound
U	Upper bound

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Laínez-Aguirre, J.M.; Puigjaner, L.

2015, XX, 309 p. 99 illus., Hardcover

ISBN: 978-3-319-10219-1