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Designing Multinational Value-Creating Supply Chain Networks for the Process Industry

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Abstract. This paper presents a multi-period mathematical programming model to design multinational production-distribution networks for process industry companies. The model is based on the mapping of the industry manufacturing process onto potential production-distribution facility locations, platforms and systems. The industrial process is defined by a directed multigraph of production and storage activities and by many-to-many recipes. Each facility may be transformed in time, and its capacity is specified by selecting facility platform and production-distribution system options. The objective is to maximize the economic value added of the multinational company in a predetermined currency. The methodology is illustrated by applying it to the case of the pulp and paper industry.

Keywords. Supply chain network design, multinational companies, mathematical programming, process industry, pulp and paper industry.

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1. Introduction

During the last decades, the world has seen considerable economic and commercial changes characterized by industry consolidation and market globalization. Research on Supply Chain Network (SCN) design has initially focused on domestic facility location and capability decisions based on cost minimisation strategies. However, with the additional challenges brought by the development of international trade, both academics and practitioners became aware of the importance of considering international factors, such as the comparative advantage of nations, exchange rates, tariffs, transfer prices and income taxes, explicitly in their SCN design methodologies as well as shifting from cost-driven decisions to value creation objectives. Globalization has led to hypercompetition, increased production resource prices and decreased finished product prices, and these trends are likely to continue in the future. In this context, the periodic reengineering of a company multinational supply chain network is crucial to maintain profitability, and in some cases to allow survival.

When designing production-distribution networks, the nature of the manufacturing processes involved may affect the modeling approach depending on if the processes are convergent (automobile, computer and apparel industries), divergent (lumber and meat industries), or “many-to-many” (pharmaceutical, chemical and several other process industries). In addition, the design problem in a purely make-to-stock industry is very different from the problem found in a highly customized make-to-order products industry. This paper presents a modeling approach for designing international many-to-many production-distribution networks. The SCN design model proposed is based on the mapping of a conceptual activity graph, depicting supply chain processes, onto potential platforms and systems associated to production-distribution sites. Its objective is to maximize corporate value added over a planning horizon, based on a performance measurement framework embedding accepted financial, accounting as well as logistic costs measurement concepts. The business environment is considered as deterministic, but several plausible future scenarios can be examined to obtain more robust designs. The methodology is illustrated by applying it to the case of the pulp and paper industry.

The paper is organized as follows. Section 2 presents a review of the relevant literature, section 3 the modeling approach and modeling constructs used, and section 4 the mathematical programming model formulated. Section 5 describes the case studied and discusses the solution of the model. Finally, a conclusion is provided in section 6.

2. Literature Review

Considerable work has been done to extend the location-allocation model proposed in the seminal paper of Geoffrion and Graves (1974) on the design of domestic single-echelon single-period production-distribution networks. A review of most of these extensions is found in Klose and Drexl (2005). The importance of capacity as a decision variable in location-allocation problems was recognized early. However, explicitly integrating capacity decisions as SCN design variables is more recent (Eppen *et al.*,1989; Verter and Dincer, 1995; Paquet *et al.*, 2004; Amrani *et al.*, 2010). In most of the literature, it is also implicitly assumed that the activities performed on a given site are predetermined. Lakhal *et al*. (1999) used an activity graph to map the succession of sourcing, manufacturing and distribution activities in a supply chain, and they propose a model to optimize the mapping of activities on SCN locations. A SCN design model based on activity graphs was subsequently proposed by Vila *et al*. (2006). Several extensions were also proposed to take international factors into account. Literature reviews of multinational SCN design models are found in Goetschalckx *et al*. (2002), Meixell and Gargeya (2005) and Melo *et al*. (2009). Some effort has also been devoted to the modeling of uncertain parameters, especially demand, prices and exchange rates. A review of this literature is provided in Klibi *et al.*, 2010.

A large body of work also exists on process industry supply chain optimization. One of the earliest papers in this field is by Brown *et al*. (1987) who developed a location-allocation model for the biscuit division of Nabisco. Sahinidis *et al*. (1989), Sahinidis and Grossmann (1991) studied a multi-period model for the selection of chemical processes and capacity expansion. A bi-level decomposition algorithm was subsequently proposed by Iyer and Grossmann (1998) to solve the same problem. Other related industrial applications and models are found in Bok *et al*. (2000), Berning *et al*. (2002), Kallrath (2002), Grunow *et al*. (2003), Shah (2005) and Meijboom and Obel (2007).

Some network design models were also developed for the pulp and paper industry. This industry is capital intensive and the impact of investment decisions must be assessed for the whole network over long planning horizons (Martel *et al.*, 2005). Benders *et al*. (1981) explains how International Paper analysed and solved its network design problems with mathematical programming models. Philpott and Everett worked with Fletcher Challenge subsidiaries in Australia and Canada to develop three models known as PIVOT, SOCRATES and COMPASS, published respectively in Philpott and Everett (2001), Everett *et al*. (2000) and Everett *et al*. (2001). The successful implementation of PIVOT, which aimed to rationalize domestic pulp and paper production costs, led to the development of SOCRATES and COMPASS, which are concerned with strategic decisions to upgrade and convert existing paper machines in order to improve quality and to be able to produce different grades of paper. They provide capital and production plans that maximize discounted annual earnings over a planning horizon. Weigel *et al*. (2009) proposed a static design model for pulp and paper plants with multiple fibre suppliers, technologies and recipes. A review and analysis of network design needs for the industry is found in Martel *et al*. (2005).

This paper proposes an integrated multi-period strategic design model to find the best SCN structure that a multinational process industry company should deploy to deal with its current and future business environment. To simplify the presentation, the model formulated is deterministic, but its transformation into a scenario based stochastic program with recourse, using the approach proposed by Santoso *et al*. (2005), is straightforward. The model is extensively tested with a realistic pulp and paper company case, and sensitivity analysis is performed on uncertain parameters such as exchange rates, market prices and demands to assess the robustness of the optimal SCN designs obtained.

3. Modeling Approach

The model proposed here may be seen as an extension of the models presented by Martel (2005), Vila *et al*. (2006) and Weigel *et al*. (2009) to consider a multi-period planning horizon, a generic many-to-many production context, and the value creation process in an international SCN. In SCN design, strategic investment decisions are concerned with capacity acquisition and resource deployment. The purpose of these decisions is to increase the value of the firm in the long term and this cannot be done without considering their impact on the daily operations of the company. This means that the revenues and costs generated by using SCN resources must be anticipated and considered explicitly in the design model.

Planning horizon

In capital intensive industries, building a new plant, reconfiguring an existing plant or even transferring activities between plants may take several years. It is therefore important to consider a multi-period planning horizon T in the design model. To facilitate discounting and income tax calculations, it is convenient to use yearly planning periods $t \in T$. The planning horizon is also partitioned into planning cycles $c \in C$, corresponding to subsets of adjacent periods $T_c \subseteq T$ at the beginning of which SCN design decisions may be made. We assume that the number of years in these planning cycles is sufficiently large to cover the implementation lead time of a potential plant. The planning cycles defined do not necessarily have the same length, which helps reducing the complexity of the model. In what follows, we use $c(t)$ to denote the cycle including planning period t, and $t(c)$ to denote the first period of planning cycle c.

Activity graph, systems and recipes

In the process industry, the value creation process can usually be represented by a directed activity graph (Dogan and Goetscalckx, 1999; Philpott and Everett, 2001; Vila *et al.*, 2006). Each value creation activity is associated to a node and it is characterized by a set of recipes that describe how inputs are transformed into outputs using durable resources. A typical activity graph for the pulp and paper industry is illustrated in *Figure 1*. In an activity graph, the set of nodes $A = \{a\}$ corresponds to activities, and the set of directed arcs $\Psi = \{(a, a')\}$ represents product flows between activities. The root node (a = 1) is usually associated to the supply market and the sink node ($a = \bar{a} = |A|$) to the sales market. Products can be considered specifically or aggregated into families manufactured by the same durable resources or supplied by the same source. In our model, the set of *products* P considered may include a mixture of individual products and product aggregates. Each activity $a \in A - \{1, \bar{a}\}$ has a set of input products $P_a^{in} \subset P$ and a set of output products $P_a^{out} \subset P$.

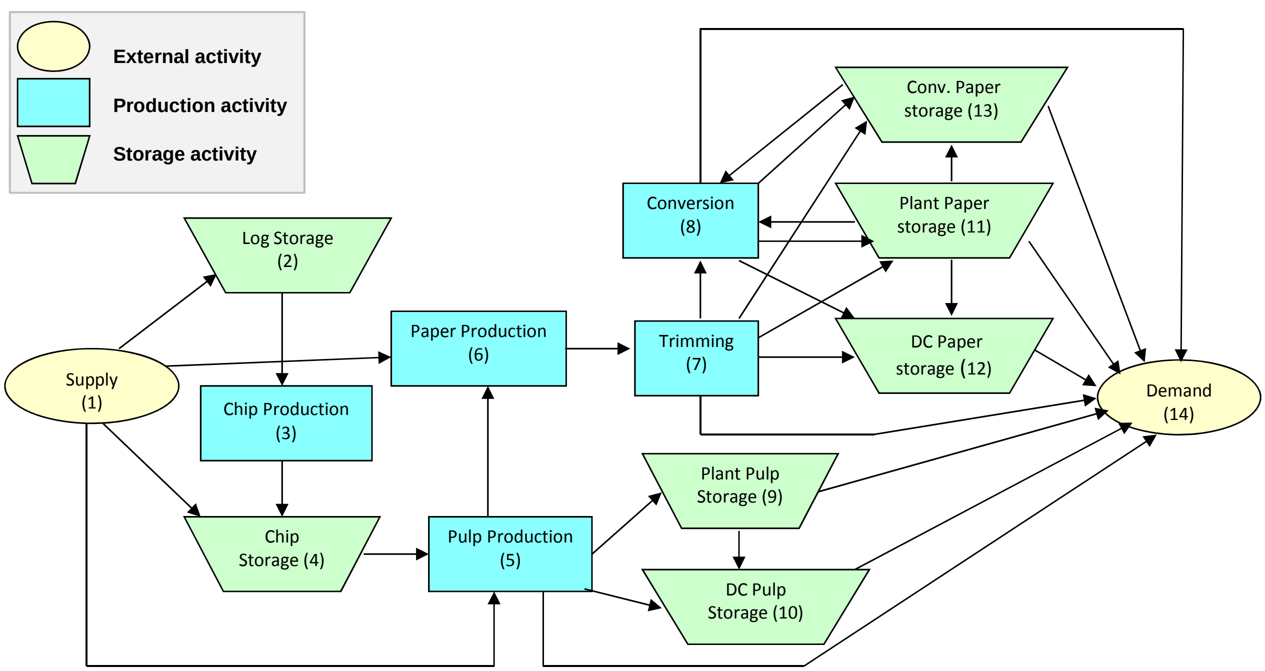


***Figure 1*: Activity Graph for a Pulp and Paper Company**

Durable resources include systems and shared resources. A system $m \in M$ may be seen as a production or storage equipment. Shared resources $w \in W$ are mainly composed of highly-skilled labour that can operate on different systems. Durable resources are used to perform activities. An activity may be performed by several systems, but a system m can perform a single activity $a(m)$. A system $m \in M$ used to perform activity $a(m)$ has input products $P_m^{in} \subset P_{a(m)}^{in}$ and output products $P_m^{out} \subset P_{a(m)}^{out}$. Production systems $m \in M^{prod}$ are characterized by the set of recipes R_m they can realize, and each recipe $r \in R_m$ is specific to the system $m(r)$ that uses it. A recipe $r \in R_m$ is defined by a set of inputs $P_{(r)}^{in} \subset P_{m(r)}^{in}$ and a set of outputs $P_{(r)}^{out} \subset P_{m(r)}^{out}$. We assume that one of these outputs is the *main*-product made with the recipe and that the others are co-products. We also define a measuring unit q_r which may be seen as the minimal production time required to run a recipe or simply as a reference time unit for recipes, expressed in standard time units (hours, shifts, etc.). In order to model 'many-to-many' recipes, we define g_{pr}^{in} as the quantity of input product $p \in P_{(r)}^{in}$ used by recipe r during the time q_r and, similarly, we define g_{pr}^{out} for output products $p \in P_{(r)}^{out}$. For storage systems $m \in M^{stor}$, since there is no product transformation, there is a single recipe $r(m)$ with $g_{pr(m)}^{in} = g_{pr(m)}^{out} = 1$ for all $p \in P_{(r(m))}^{in} = P_{(r(m))}^{out}$. *Figure 2* illustrates how these concepts contribute to model an activity.

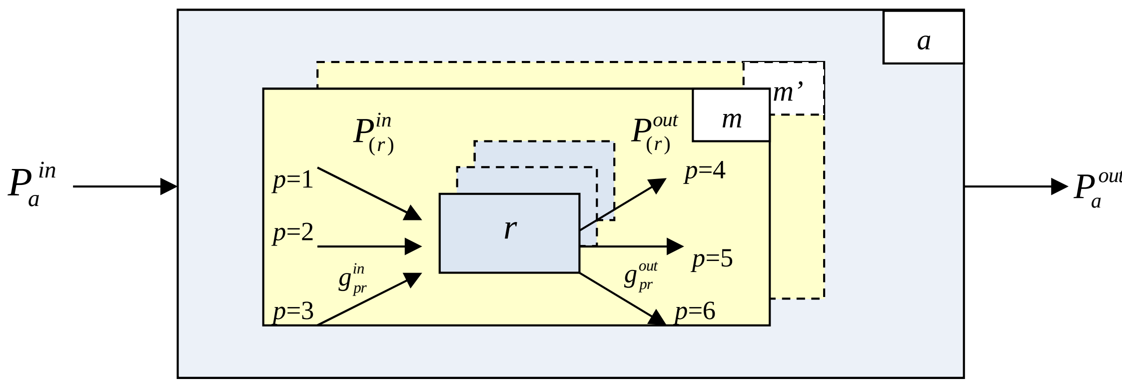


***Figure 2*: 'Many-to-many' Activity Structure**

A large number of recipes may be required in a manufacturing process. These recipes can be considered explicitly in tactical or operational planning models, but at the design level using all of them would yield an intractable model. For this reason, we define meta-recipes aggregating all the recipes capable of producing a given main-product on a given system. Let's partition R_m into subsets $R_{(\bar{r})}$, $\bar{r} \in \bar{R}_m$, such that each $r \in R_{(\bar{r})}$ has the same main-product. Then the meta-recipe $\bar{r} \in \bar{R}_m$ has a set of inputs $\bar{P}_{(\bar{r})}^{in} = \bigcup_{r \in R_{(\bar{r})}} P_{(r)}^{in}$ and a set of outputs $\bar{P}_{(\bar{r})}^{out} = \bigcup_{r \in R_{(\bar{r})}} P_{(r)}^{out}$, and it is specific to the system $m(\bar{r})$ that uses it. Moreover, the quantity of inputs and outputs it consumes/produces during one unit of time depends on the frequency of use of the recipes $r \in R_{(\bar{r})}$. These input/output quantities are provided by the following weighted averages:

$$\bar{g}_{p\bar{r}}^{in} = \sum_{r \in R_{(\bar{r})}} \theta_r \frac{g_{pr}^{in}}{q_r},\ p \in \bar{P}_{(\bar{r})}^{in}, \bar{r} \in \bar{R}_m, m \in M^{prod}$$

$$\bar{g}^{out}_{p\bar{r}} = \sum_{r \in R_{(\bar{r})}} \theta_r \frac{g^{out}_{pr}}{q_r},\ p \in \bar{P}^{out}_{(\bar{r})}, \bar{r} \in \bar{R}_m, m \in M^{prod}$$

where θ_r is the proportion of the time where recipe $r \in R_{(\bar{r})}$ is used to make output products $\bar{P}^{out}_{(\bar{r})}$. These proportions can be estimated from historical production data, if available, or by setting $\theta_r = 1/|R_{(\bar{r})}|,\ r \in R_{(\bar{r})}$.

The notation required to model activity graphs, systems and recipes is the following:

A = Set of activities ($a \in A$).

A^{prod} = Set of production activities ($A^{prod} \subseteq A$).

A^{stor} = Set of storage activities ($A^{stor} \subseteq A$).

A^{in}_a = Set of immediate predecessors of activity a ($A^{in}_a \subseteq A$).

A^{out}_a = Set of immediate successors of activity a ($A^{out}_a \subseteq A$).

P = Set of products ($p \in P$).

P^{in}_a = Set of input products of activity a ($P^{in}_a \subseteq P$).

P^{out}_a = Set of output products of activity a ($P^{out}_a \subseteq P$).

M = Set of all systems, including original and reconfigured systems ($m \in M$).

M^{prod} = Set of production systems ($M^{prod} \subseteq M$).

M^{stor} = Set of storage and handling systems ($M^{stor} \subseteq M$).

W = Set of shared resources ($w \in W$).

R [$\bar{R}$] = Set of recipes ($r \in R$) [meta-recipes ($\bar{r} \in \bar{R}$)].

R_m [$\bar{R}_m$] = Set of system $m \in M$ recipes [meta-recipes ($\bar{r} \in \bar{R}_m$)].

$P^{in}_{(r)}$ [$\bar{P}^{in}_{(\bar{r})}$] = Set of input products of recipe r ($P^{in}_{(r)} \subseteq P^{in}_{m(r)}$) [meta-recipe $\bar{r}$].

$P^{out}_{(r)}$ [$\bar{P}^{out}_{(\bar{r})}$] = Set of output products of recipe r ($P^{out}_{(r)} \subseteq P^{out}_{m(r)}$) [meta-recipe $\bar{r}$].

q_r = Unit processing time for recipe r expressed in standard time units.

q_{pm} = Capacity consumption rate per unit of product p for storage system $m \in M^{stor}$.

g^{in}_{pr} [$\bar{g}^{in}_{p\bar{r}}$] = Quantity of input $p \in P^{in}_{(r)}$ used with recipe r during one processing unit q_r [aggregate quantity of input p for meta-recipe $\bar{r}$].

g^{out}_{pr} [$\bar{g}^{out}_{p\bar{r}}$] = Quantity of output $p \in P^{out}_{(r)}$ produced with recipe r during one processing unit q_r [aggregate quantity of output p for meta-recipe $\bar{r}$].

g_{wm} = Amount of shared resource w required to operate system $m \in M^{prod}$ during one standard time unit.

b_{wt} = Upper bound on the availability of shared resource w during period t.

$X_{\bar{r}t}$ = Production level with meta-recipe $\bar{r}$ during period t, expressed in standard time units.

Production-distribution network structure

Activities are performed in the facilities (plants, warehouses, etc.) of the various locations of the potential supply chain network. We distinguish three location types: external raw material suppliers ($v \in V$), potential internal sites ($s \in S$) and demand zones ($d \in D$). These locations are geographically dispersed over several countries $o \in O$. Internal sites correspond to existing facilities owned by the company, to facilities that could be bought or rented, to sites where it is possible to build a plant or warehouse, or to potential subcontractor facilities. They are subdivided into production-distribution sites (S^{pd}) which could accomodate production and/or distribution activities, and distribution sites (S^{d}) which could be used only for distribution activities. A site mission can be restricted by limiting the types of system it can implement. External suppliers $v \in V$ supply raw materials $RM \subset P$ and finished products $FP \subset P$ are sold to demand zones $d \in D$.

The purpose of the design methodology proposed in this paper is to find the optimal SCN structure by mapping the activity graph onto potential physical locations, which yields a network flow model of the form illustrated in *Figure 3*. The arcs of the network describe product movements between activities performed in different sites or in the same site. The variables $F_{p(n,a)(n',a')t}$ are used to define the flow of product p between location-activity pairs (n,a) and (n',a') during period t. Flows between two activities performed in the same site are associated to handling systems, whereas flows between activities in different locations are associated to transportation means (truck, rail, etc.). It is assumed that for-hire transportation is used so that transportation capacity on arcs is unlimited, and the mean of transportation to use on any specific arc can be predetermined. A product p can be supplied to location n from a set N_{pn}^{in} of origins, and a product p can be shipped from location n to the set N_{pn}^{out} of destinations.

The following notation is used in order to model the SCN structure:

O	=	Set of countries covered by the SCN ($o \in O$, $o(n)$ = country of location n).
N	=	Set of network locations ($n \in N = V \cup S \cup D$).
N_{pn}^{out}	=	Potential locations (output destinations) which can receive product p from node $n \in S \cup V$ ($N_{pn}^{out} \subseteq S \cup D$).
N_{pn}^{in}	=	Potential locations (input sources) which can ship product p to node $n \in S \cup D$ ($N_{pn}^{in} \subseteq V \cup S$).
S^{pd}	=	Set of production-distribution sites ($S^{pd} \in S$)
S^{d}	=	Set of distribution sites ($S^{d} \in S$ / $S^{d} \cup S^{pd} = S$)
RM	=	Set of raw materials ($RM \subseteq P$).

FP = Set of finished products ($FP \subseteq P$).

$F_{p(n,a)(n',a')t}$ = Flow of product $p \in P$ between activity a at location $n \in V \cup S$ and activity a' at location $n' \in S \cup D$ during period t.

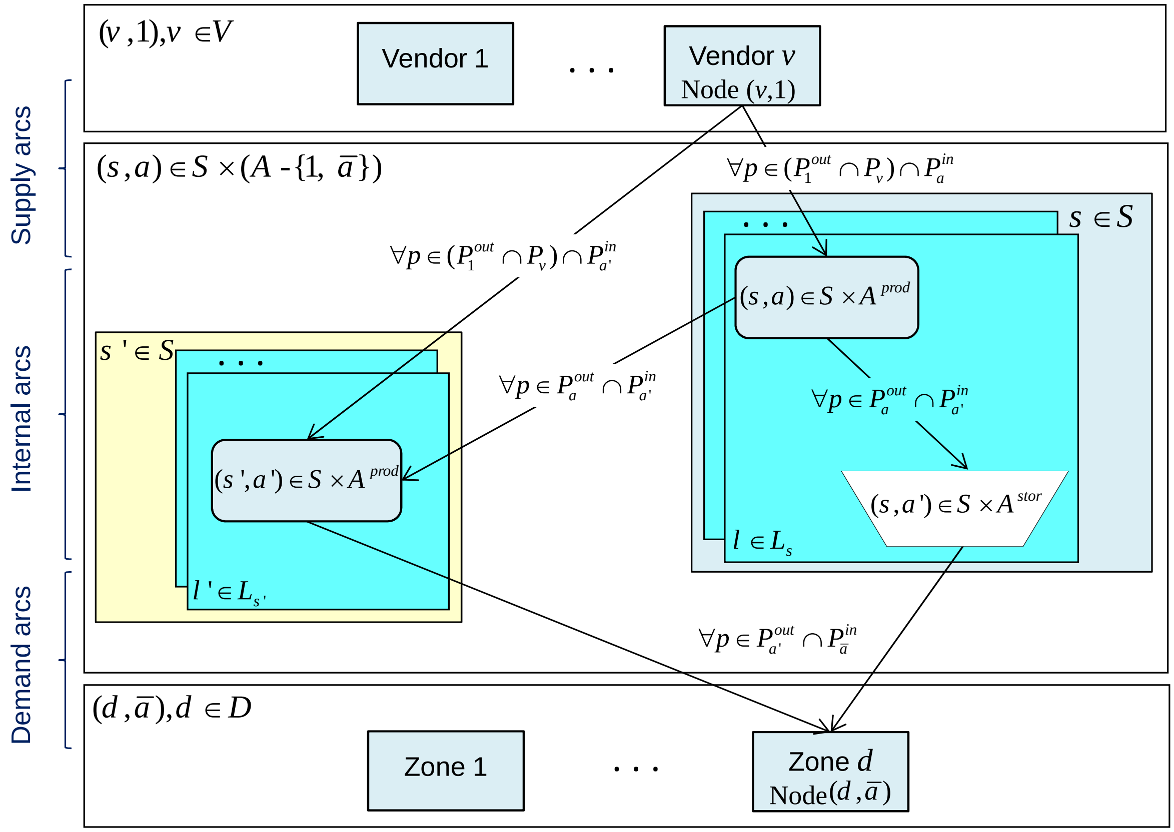


***Figure 3*: Mapping the Activity Graph onto Potential Locations for a Time Period**

Modeling site platforms and capacity options

In SCN design, configuration decisions may concern all the company facilities or only a part of them. Moreover, for a given site, reengineering decisions may include all the existing equipments or only some of them, especially for capital intensive industries, such as the pulp and paper industry, where equipment acquisition and reconfiguration are important strategic decisions. The site *platform* and the *system* concepts are introduced to take into account the technical and economic characteristics of reconfiguration possibilities. Platforms are associated to buildings and systems to equipments or facilities providing capacity.

As illustrated in *Figure 4*, a platform $l \in L$ on a site $s \in S$ is composed of two parts: a fixed part, which must not be modified and a variable part defining an area which could be reengineered. Therefore, the systems implemented in the fixed part are predetermined and are characterized by the products they can make/stock as well as their capacity per period, expressed in standard units. On the other hand, the variable part is defined by the area E_l available for the installation of a set of potential alternative systems. It is important to mention that a platform may include only a fixed part corresponding to an *a priori* opened site, or a variable part corresponding to a full reconfiguration. Finally, several platforms $l \in L_s$ can be considered for each site s, including potential platforms corresponding to new construction or reconfiguration opportunities, as well as a *status-quo* platform if there is already a facility on the site. Each platform l is associated to a specific site $s(l)$.

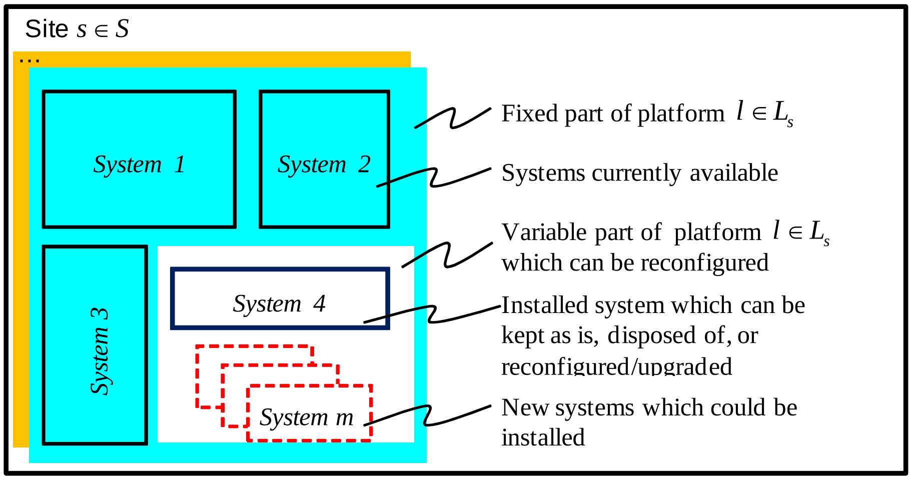


***Figure 4*: Illustration of the Site Platform Concept**

Similarly, systems are classified into original systems M^{or} and upgraded (reconfigured) systems M^{up}, with $M = M^{or} \cup M^{up}$. An original system $m \in M^{or}$ is a new production/storage technology which could replace an existing system or be added in the variable part of a platform. On the other hand, an upgraded system $m \in M^{up}$ is a transformation of an installed system, and it can therefore be selected at the beginning of a cycle only if its predecessor is installed. This classification is introduced to consider capacity expansion and/or upgrade decisions that the company may want to postpone to latter cycles to adapt gradually to the evolution of the business environment. A capacity option can also be abandoned if the company finds that the business environment is unfavourable to invest. In addition, since intensive capital investment decisions are considered, the introduction of this concept allows the company to separate large investment projects into several steps, and to implement them over several planning cycles. This takes even more importance when uncertainty is considered explicitly in order to model *real options* (Trigeorgis, 1996). In order to specify precedence relations, we define a set M_m^{out} of immediate successors for any system m.

Alternative capacity options can also be defined to reflect economies of scale. Hence, the set $M_l^{or} \subset M^{or}$ of original systems which can be implemented in platform l, may contain several systems that use the same technology (or that correspond to the same type of equipment) but have different capacities. In this case, when dealing with a potential equipment replacement/reconfiguration, these systems cannot be selected at the same time, which leads to the definition of mutually exclusive system subsets ME_l^{γ}, $\gamma = 1,\ldots, \Gamma_l$, for some platforms $l \in L_s$. Each system m is associated to a specific platform $l(m)$, and thus to a single site $s(m) = s(l(m))$. For each period $t \in T$, it is characterized by a capacity b_{mt}, stated in standard time or space units. In addition, each system requires a floor space e_m in order to be installed.

The same modeling approach is applied for platforms, to represent different expansion possibilities defined on sets L^{or} and L^{up} of original and upgraded (reconfigured) platforms for a given site, and a set L_l^{out} of immediate successors for any platform l with further reconfiguration options.

The following notation is used to define site platform and system options:

L = Set of all platforms including original and reconfigured platforms.

L_s = Set of alternative (potential) platforms for site s ($l \in L_s$). By convention, if there is a facility on site s, the index $l = 1$ is given to the current platform ($L = \cup_{s \in S} L_s$).

L_s^{or} = Set of *original* platforms for site s ($L_s^{or} \subseteq L_s$).

L_s^{up} = Set of *upgrade* platforms for site s ($L_s^{up} \subseteq L_s$).

L_l^{out} = Set of immediate successors of platform l in the platform option tree.

M_l = Set of alternative (potential) systems for platform l.

M_s = Set of alternative (potential) systems for site s ($M_s = \cup_{l \in L_s} M_l$).

M_{as} = Set of systems which can be used to perform activity a on site s.

M^{or} = Set of *original* systems ($M^{or} \subseteq M$).

M^{up} = Set of *upgraded* systems ($M^{up} \subseteq M$).

M_m^{out} = Set of immediate successors of system m in the system option tree.

ME_l^{γ} = Mutually exclusive system subsets in M_l^{or} ($\gamma = 1,\ldots, \Gamma_l$).

Γ_l = Number of mutually exclusive system subsets in M_l^{or}.

M_w = Set of alternative (potential) production systems which require the use of shared resource w ($M_w \subset M$).

W_s = Set of shared resources used in site s.

E_l = Total area of the variable part of platform l.

e_m = Area required to install system m.

b_{mt} = Capacity provided by system m for period t, expressed in standard time units for production systems and in space units for storage systems.

Z_{mc}^{+} = Binary variable equal to 1 if system m is installed at the beginning of cycle c and to 0 otherwise.

Z^-_{mc} = Binary variable equal to 1 if system *m* is removed at the beginning of cycle *c* and to 0 otherwise.

Z_{mc} = Binary variable equal to 1 if system *m* is operational during cycle *c* and to 0 otherwise.

Y^+_{lc} = Binary variable equal to 1 if platform *l* is installed on site *s*(*l*) at the beginning of cycle *c* and to 0 otherwise.

Y^-_{lc} = Binary variable equal to 1 if platform *l* is replaced in site *s(l)* at the beginning of cycle *c* and to 0 otherwise.

Y_{lc} = Binary variable equal to 1 if platform *l* is in use on site *s*(*l*) during cycle *c* and to 0 otherwise.

x_{wt} = Amount of shared resource *w* required during period *t*, expressed in standard time units.

Note that a site *s* is not used in cycle *c* when $Y_{lc} = 0\ \forall l \in L_s$, i.e. when no platform is installed.

Modeling external activities

External vendors are classified according to the products *p* and the sites *s* they can supply, and we assume that a vendor $v \in V_{ps}$ has a limited capacity $\hat{b}^{\max}_{pvt}$ for each period *t*. Also, we assume that sourcing contracts specify minimum quantities $\hat{b}^{\min}_{vst}$ that must be supplied to a site *s* from a given vendor. The *hat* on the capacity parameter indicates that its value is based on a long term forecast or agreement that is subject to modification or update at a later date. Note that in what follows we place a dash ‘ $\bar{\ }$ ’ above aggregated parameters and a hat “^” on forecasted parameters.

The demand zones set *D* is also partitioned into product-market segments D_p. Each product-market segment $d \in D_p$ is characterized by a product $p \in FP$, a product price $\bar{\pi}_{pdt}$ and a service policy defined by the maximum distance allowed between customers and potential distribution centers ($s \in S$). We assume that the largest market share (demand) $\hat{x}^{\max}_{pdt}$ the company can expect for product *p* in demand zone *d* during period *t* can be forecasted, and that the company has minimum market penetration objectives $\hat{x}^{\min}_{pdt}$ for each of its product-markets.

The notation required to model supply and demand activities is the following:

D_p = Demand zones requiring product $p \in FP$ ($D_p \subset D$).

D_{ps} = Demand zones requiring product $p \in FP$ that can be served from site *s* ($D_{ps} \subset D$).

V_p = Vendors of raw material $p \in RM$ ($V_p \subset V$).

V_{ps} = Vendors of raw material $p \in RM$ which can supply site $s \in S$ ($V_{ps} \subset V$).

$\overline{\pi}_{pdt}$ = Amount received for the sale of product p to demand zone d during period t.

$\hat{x}_{pdt}^{\max}$ = Largest expected demand for product p in demand zone d during period t.

$\hat{x}_{pdt}^{\min}$ = Minimum market penetration objective for product p in zone d during period t.

$\hat{b}_{pvt}^{\max}$ = Upper bound on the quantity of raw material p which can be supplied by vendor v in period t.

$\hat{b}_{vst}^{\min}$ = Lower bound on the total quantity of raw material that must be supplied from vendor v to site s during period t (imposed by a vendor contract).

ϕ_{pvst}^{v} = Unit cost of the flow of product p between vendor v and site s paid by destination s during period t (this cost includes the product price and variable transportation costs).

U_{vc} = Binary variable equal to 1 if supplier v is selected in planning cycle c and to 0 otherwise.

4. Mathematical Programming Model

The concepts presented so far are necessary to understand the SCN optimization model proposed in this section. Basically, the model specifies the network structure which should be deployed in the long term to maximize value creation, taking into account international factors, sales market opportunities and network resources capabilities. We should underline that the periodic flow and production variables included in the model are not design decisions, and thus that they are not implemented in practice. They are introduced in the model to calibrate the network capacity, to ensure flow equilibrium, and to anticipate operational revenues and costs. In addition to the notation already defined, additional notation will be introduced when required.

Supply and sales market constraints

The raw material supply market corresponds to the root node (a = 1) of the activity graph. The set of immediate successors A_1^{out} defines production-storage activities performed in different sites $s \in S$ and requiring some raw materials as inputs. Lower and upper bounds on inbound flows from suppliers are defined as follows:

$$\sum_{a \in A_1^{out}} \sum_{s \in N_{pv}^{out}} F_{p(v,1)(s,a)t} \leq \hat{b}_{pvt}^{\max} U_{vc(t)}, \qquad p \in P_1^{out}, v \in V_p, t \in T \tag{1}$$

$$\sum_{a \in A_1^{out}} \sum_{p \in RM} F_{p(v,1)(s,a)t} \geq \hat{b}_{vst}^{\min} U_{vc(t)}, \qquad s \in N_v^{out}, v \in V, t \in T \tag{2}$$

Similarly, the sales market corresponds to the sink node (a = ā) of the activity graph and the outbound flows of finished products (*FP*) sent from distribution sites to demand zones must respect the following potential market demand constraints:

$$\sum_{a \in A_{\bar{a}}^{in}} \sum_{s \in N_{pd}^{in}} F_{p(s,a)(d,\bar{a})t} \le \hat{x}_{pdt}^{\max}, \qquad p \in P_{\bar{a}}^{in}, d \in D_p, t \in T \tag{3}$$

Minimum market penetration targets must also be respected:

$$\hat{x}_{pdt}^{\min} \le \sum_{a \in A_{\bar{a}}^{in}} \sum_{s \in N_{pd}^{in}} F_{p(s,a)(d,\bar{a})t}, \qquad p \in P_{\bar{a}}^{in}, d \in D_p, t \in T \tag{4}$$

Site platform and capacity option constraints

The following constraints must be included in the model to ensure that at most one original platform $l \in L_s^{or}$ is selected for each site over the planning horizon:

$$\sum_{c \in C} \sum_{l \in L_s^{or}} Y_{lc}^{+} \le 1, \qquad s \in S \tag{5}$$

We impose that any site cannot be closed more than once during the planning horizon:

$$\sum_{c \in C} \sum_{l \in L_s} Y_{lc}^{-} \le 1, \qquad s \in S \tag{6}$$

We also need to ensure that no more than one platform is operational on a site during a cycle:

$$\sum_{l \in L_s} Y_{lc} \le 1, \qquad s \in S, c \in C \tag{7}$$

The following constraints must be added to ensure that, in each cycle, the area required by the selected systems does not exceed the area available in the selected platform, and that mutually exclusive systems are not selected together during the planning horizon:

$$\sum_{m \in M_l} e_m Z_{mc} - E_l Y_{lc} \le 0, \qquad l \in L, c \in C \tag{8}$$

$$\sum_{c \in C} \sum_{m \in ME_l^{\gamma}} Z_{mc}^{+} \le 1, \qquad l \in L, \gamma = 1,...,\Gamma_l \tag{9}$$

In addition, the following constraints must be added to ensure that any upgraded platform or system cannot be installed in a given cycle unless its immediate predecessor was installed during the previous cycle, and not closed at the end of the previous cycle:

$$\sum_{l' \in L_l^{out}} Y_{l'c}^{+} \le Y_{l(c-1)} - Y_{lc}^{-}, \qquad l \in L, c \in C \tag{10}$$

$$\sum_{m' \in M_m^{out}} Z_{m'c}^{+} \le Z_{m(c-1)} - Z_{mc}^{-}, \qquad m \in M, c \in C \tag{11}$$

Finally, integrity constraints are required to ensure that when the decision to install a given platform or system is taken for any cycle, the latter will be operational in that cycle. Conversely, when a closing decision is made for a given cycle, the platform or system concerned must not be used for the rest of the horizon. Moreover, when an optional platform or system is selected, it replaces its predecessor without forcing its closing. Otherwise, closing costs would be computed. These constraints may be stated as follows:

$$Y_{lc} + \sum_{l' \in L_l^{out}} Y_{l'c}^{+} + Y_{lc}^{-} - Y_{lc}^{+} - Y_{l(c-1)} = 0, \; l \in L, c \in C \tag{12}$$

$$Z_{mc} + \sum_{m' \in M_m^{out}} Z_{m'c}^{+} + Z_{mc}^{-} - Z_{mc}^{+} - Z_{m(c-1)} = 0, \; m \in M, c \in C \tag{13}$$

Flow and inventory constraints

For production activities in a site, the material processed must not exceed what is received from preceding activities, i.e.:

$$\sum_{m \in M_{as}} \sum_{\bar{r} \in \bar{R}_m | p \in \bar{P}_{(\bar{r})}^{in}} \bar{g}_{p\bar{r}}^{in} X_{\bar{r}t} \le \sum_{a' \in A_a^{in}} \left(F_{p(s,a')(s,a)t} + \sum_{n \in N_{ps}^{in}} F_{p(n,a')(s,a)t} \right), \; a \in A^{prod}, p \in P_a^{in}, s \in S^{pd}, t \in T \tag{14}$$

and the outflow of a production activity must not exceed the amount produced, i.e:

$$\sum_{a' \in A_a^{out}} \left(F_{p(s,a)(s,a')t} + \sum_{n' \in N_{ps}^{out}} F_{p(s,a)(n',a')t}\right) \le \sum_{m \in M_{as}} \sum_{\bar{r} \in \bar{R}_m | p \in \bar{P}_{\bar{r}}^{out}} \bar{g}_{p\bar{r}}^{out} X_{\bar{r}t}, \quad a \in A^{prod}, p \in P_a^{out}, s \in S^{pd}, t \in T \tag{15}$$

Two types of stocks are considered in the model. First, we specify the level of *strategic inventory* required in distribution centers at the end of each period to face increasing demands in subsequent periods, or to prepare for planned capacity shutdowns. Second, *safety and order cycle stocks* are considered. The level of the later depends on the inventory management policy of the company and on the ordering behaviour of customers, and it is calculated using the inventory turnover ratio of each products.

The following notation is required to model inventories:

ρ_{pst} = Number of periods of cycle and safety stock kept on average for product p in site s during period t (inverse of the inventory turnover ratio).

β_p = Order cycle and safety stock (maximum level)/(average level) ratio for product p.

I_{pmst} = Strategic inventory of product p stored in site s with system $m \in M^{stor}$ at the end of period t.

$\bar{I}_{pst}$ = Average level of the order cycle and safety stock of product p in site s during t.

The following equations account for additions and withdrawals from strategic inventories during each period for production-distribution centers and distribution centers respectively:

$$\sum_{m\in M_l} I_{pmst} + \sum_{a'\in A_a^{out}}\left(F_{p(s,a)(s,a')t} + \sum_{n'\in N_{ps}^{out}} F_{p(s,a)(n',a')t}\right) = \sum_{m\in M_l} I_{pmst-1} + \sum_{a'\in A_a^{in}}\left(F_{p(s,a')(s,a)t} + \sum_{n\in N_{ps}^{in}} F_{p(n,a')(s,a)t}\right), a\in A^{stor}, p\in P_a^{in}, l\in L_s, s\in S^{pd}, t\in T \tag{16}$$

$$\sum_{m\in M_l} I_{pmst} + \sum_{a'\in A_a^{out}}\sum_{n'\in N_{ps}^{out}} F_{p(s,a)(n',a')t} = \sum_{m\in M_l} I_{pmst-1} + \sum_{a'\in A_a^{in}}\sum_{n\in N_{ps}^{in}} F_{p(n,a')(s,a)t}, a\in A^{stor}, p\in P_a^{in}, l\in L_s, s\in S^{d}, t\in T \tag{17}$$

The average level $\bar{I}_{pst}$ of the order cycle and safety stock of product p in site s during period t can be calculated with the following expressions:

$$\bar{I}_{pst} = \rho_{pst}\left[\sum_{a'\in A_a^{out}}\left(F_{p(s,a)(s,a')t} + \sum_{n'\in N_{ps}^{out}} F_{p(s,a)(n',a')t}\right)\right], a\in A^{stor}, p\in P_a^{out}, s\in S^{pd}, t\in T \tag{18}$$

$$\bar{I}_{pst} = \rho_{pst}\left[\sum_{a'\in A_a^{out}}\sum_{n'\in N_{ps}^{out}} F_{p(s,a)(n',a')t}\right], a\in A^{stor}, p\in P_a^{out}, s\in S^{d}, t\in T$$

The maximum level of cycle and safety stocks to be stored in a period is obtained by multiplying the average inventory level $\bar{I}_{pst}$ by an empirical amplification factor β_p (Martel, 2005). In practice, the parameters ρ_{pst} and β_p are estimated statistically from the company data on the inventory held in its facilities. It is assumed that each product the company holds in a distribution center is stored using a single storage system. This yields to the following storage capacity constraints:

$$\sum_{p\in P_m^{out}} q_{pm}(I_{pms(m)t} + \beta_p \bar{I}_{ps(m)t}) \le b_{mt} Z_{mc(t)},\ m\in M^{stor}, t\in T \tag{19}$$

Production activities are also limited by system capacity and shared resources availability during a period. This leads to the following constraints:

$$\sum_{\bar{r}\in \bar{R}_m} X_{\bar{r}t} \le b_{mt} Z_{mc(t)},\quad m\in M^{prod},\ t\in T \tag{20}$$

$$x_{wt} = \sum_{m\in M_w} g_{wm} \sum_{\bar{r}\in \bar{R}_m} X_{\bar{r}t} \le b_{wt},\quad w\in W, t\in T \tag{21}$$

Modeling economic value added

In order to model the economic value added by international logistic networks, several assumptions must be made:

- The prices and costs associated with the nodes of the network are given in local currency. The costs associated with the arcs of the network are given in source currency. Exchange rates are known and constant for each period of the planning horizon.
- Each time products cross a border, tariffs and duties are charged on the flow of merchandise and these are paid by the importer. It is assumed that importers pay border tariffs based on CIF product values.
- Transportation costs on the network arcs are paid by the origin and are assumed to be linear with respect to flows.
- Transfer prices for products sent in the internal network are predetermined and they cover all upstream costs plus a margin. In order to comply with laws and regulations, the transfer price of a product shipped from a given source is the same for all destinations.
- The income taxes paid in a country are calculated on the sum of the net revenues (or loss) made by all facilities in that country. The corporate taxes of the parent company are deferred until it pays dividends, and the decision to pay dividends is independent of the design of the network.
- The accounting depreciation of assets and the financial amortization of investments are distinguished. Accounting depreciation corresponds to the devaluation of fixed assets over their *economic life* (*EL*) in order to calculate their book value for tax purposes. We assume that the straight-line depreciation method is used. Since large investments are required for systems and platforms, their value is typically depreciated over 10 to 20 years depending on the nature of the asset and the country's accounting legislation. We assume in what follows that the model's planning horizon T is shorter than the *EL* of all the platforms and systems considered. The financial amortization of investments corresponds to the annuities paid as reimbursements to capital lenders over a set of credit periods called the *financial horizon*. This financial horizon (*FH*) starts at the beginning of the planning horizon and includes a number of periods equal to the weighted average of the credit periods of the company loans. We assume that acquisition and implementation costs associated to reconfiguration, expansion and closing decisions, as well as strategic inventories, are financed through loans and cash provisions over the *FH*. We also assume that the company makes these provisions in order to

equalize its financial requirements during the planning horizon, and that interest is charged on provisions, based on its weighted average cost of capital (WACC), to reflect opportunity costs.

- The costs associated to platforms and systems are captured through the use of three parameters associated to the binary variables Y_{lc}^{+} (Z_{mc}^{+}), Y_{lc}^{-} (Z_{mc}^{-}) and Y_{lc} (Z_{mc}) namely:

  A_{lc}^{+} (a_{mc}^{+}) = Fixed cost of installing platform *l* (system *m*) at the beginning of cycle *c*.

  A_{lc}^{-} (a_{mc}^{-}) = Fixed cost of closing platform *l* (system *m*) at the beginning of cycle *c*.

  A_{lt} (a_{mt}) = Fixed cost of using platform *l* (system *m*) during period *t*.

  Opening and closing costs are related to planning cycles since they are incurred only if there is a change in network structure (closing an existing facility, building or buying a new facility, changing a platform, etc.), whereas fixed operating costs are incurred in each period for any open site. Relevant fixed costs for different contexts are listed in *Table 1*. These costs are forecasts based on price indexes and inflation rates. Building, acquisition and reconfiguration costs correspond to the investment required at the beginning of a cycle to open or reconfigure a site, and set-up costs include any one-time implementation costs. Closing costs include dismissal indemnities, administrative costs, compensations given to customers, as well as any other penalties related to loss in materials and equipment value. We assume, however, that closed platforms/systems are sold by the company only at the end of the planning horizon.

- We assume that a variable production cost c_{rt} is incurred when recipe *r* is used during period *t*. For meta-recipes, the corresponding variable costs per unit time are given by:

$$\bar{c}_{\bar{r}t} = \sum_{r \in R_{(\bar{r})}} \theta_r \frac{c_{rt}}{q_r}, \quad \bar{r} \in \bar{R}_m, m \in M^{prod}$$

	Close (A_{lc}^{-})	*Use* (A_{lt})	*Open/change* (A_{lc}^{+})
Owned facility	- Closing cost	- Operating cost	- Set-up cost - Building cost - Acquisition cost - Reconfiguration cost
Rented facility	- Closing cost - Lease penalty	- Rent - Operating cost	- Set-up cost
Public facility	- Departure cost	- Usage charges - Operating cost	- Set-up cost

***Table 1*: Platform/System Fixed Costs in Different Contexts**

The company wants to maximize its economic value added over a multi-period planning horizon in a predetermined currency. The additional notation required to model costs and revenues is the following:

c_{wt} = Unit variable cost of shared resource *w* in period *t*.

$f^{h}_{paa'st}$ = Unit handling cost for the move of product *p* between activity *a* and activity *a'* on site *s* during period *t*.

f^{o}_{psnt} = Unit cost of the flow of product *p* between site *s* and location *n* paid by the origin during period *t* (this cost includes the customer-order processing cost, the shipping cost, the variable transportation cost and the inventory-in-transit holding cost).

f^{t}_{psnt} = Unit transportation cost of product *p* from site *s* to location *n* during period *t* (this cost is included in f^{o}_{psnt}).

f^{d}_{pnst} = Unit cost of the flow of product *p* between location *n* and site *s* paid by destination *s* during period *t* (this cost includes the supply-order processing cost and the receiving cost).

f^{v}_{pvst} = Unit cost of the flow of product *p* between vendor *v* and site *s* paid by destination *s* during period *t* (this cost includes the product price ϕ_{pvst} and the variable transportation cost).

h_{pst} = Unit inventory holding cost of product *p* in site *s* for period *t*.

$\bar{\pi}_{pst}$ = Average transfer price of product *p* shipped from site *s* during period *t*.

$\hat{e}_{oo't}$ = Forecasted exchange rate for period *t*, i.e. the number of units of country *o* currency by units of country *o'* currency (the index *o* = 0 is given to the country of the parent company).

δ_{pnst} = Import duty rate applied to the CIF price of product *p* when transferred from the country of node *n* to the country of site *s* for period *t*.

ω_{ot} = Income tax rate of country *o* for period *t*.

α = The discount rate used by the company, based on the weighted average cost of capital (WACC).

$\bar{\pi}_{pdt}$ = Average price of product *p* sold to demand zone *d* during period *t*.

R_{st} = Total site *s* revenues for period *t*.

C_{st} = Total site *s* expenses for period *t*.

M^{+}_{ot} = Operating profit made in country *o* during period *t*.

M^{-}_{ot} = Operating loss made in country *o* during period *t*.

Revenues and expenses incurred at different sites for a year (period) t are outlined in *Table 2*. The expression for the inflow transfer costs (a) is obtained by first converting the transfer prices and transportation costs in local currency and then by adding the applicable duties. A similar approach is used to calculate other revenues and expenses. The entries of this table can be used to calculate site revenues and expenses as follows:

$$C_{st} = (a) + (b) + (c) + (d) + (e) + (f) + (g) + (h) + (i) + (j) \qquad s \in S^{pd},\ t \in T \qquad (22)$$

$$C_{st} = (a) + (b) + (c) + (e) + (f) + (g) + (i) + (j) \qquad s \in S^{d},\ t \in T \qquad (23)$$

$$R_{st} = (k) + (l) \qquad s \in S,\ t \in T \qquad (24)$$

Operating profits or loss can then be calculated as follows:

$$M_{ot}^{+} - M_{ot}^{-} = \sum_{s \in S_o} (R_{st} - C_{st}), \qquad o \in O, t \in T \qquad (25)$$

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Planning period $t \in T$</td></tr>
<tr><td>Distribution center
($s \in S^{d}$)</td><td>Production-distribution center
($s \in S^{pd}$)</td></tr>
<tr><td rowspan="10">Expenses</td><td>a) Inflow transfer costs</td><td colspan="2">$\sum_{a,a' \in A-\{\bar{a}\}} \sum_{p \in P_{a'}^{out} \cap P_a^{in}} \sum_{s' \in N_{ps}^{in}} (1+\delta_{ps'st}) \hat{e}_{o(s)o(s')t} (\bar{\pi}_{ps't} + f_{ps'st}^{t}) F_{p(s',a')(s,a)t}$</td></tr>
<tr><td>b) Raw materials</td><td colspan="2">$\sum_{a \in A-\{1\}} \sum_{p \in P_a^{in}} \sum_{v \in V_{ps}} (1+\delta_{pvst}) \hat{e}_{o(s)o(v)t} f_{pvst}^{v} F_{p(v,1)(s,a)t}$</td></tr>
<tr><td>c) Receptions from other sites</td><td colspan="2">$\sum_{a,a' \in A-\{\bar{a}\}} \sum_{p \in P_{a'}^{out} \cap P_a^{in}} \sum_{n \in N_{ps}^{in}} f_{pnst}^{d} F_{p(n,a')(s,a)t}$</td></tr>
<tr><td>d) Production costs</td><td></td><td>$\sum_{w \in W_s} c_{wt} x_{wt} + \sum_{m \in M_s^{prod}} \sum_{\bar{r} \in \bar{R}_m} \bar{c}_{\bar{r}t} X_{\bar{r}t}$</td></tr>
<tr><td>e) Operational fixed costs</td><td colspan="2">$\sum_{l \in L_s} A_{lt} Y_{lc(t)} + \sum_{m \in M_s} a_{mt} Z_{mc(t)}$</td></tr>
<tr><td>f) Order cycle and safety stocks</td><td colspan="2">$\sum_{a \in A^{stor}} \sum_{p \in P_a^{out}} h_{pst} \bar{I}_{pst}$</td></tr>
<tr><td>g) Strategic inventory</td><td colspan="2">$\sum_{a \in A^{stor}} \sum_{p \in P_a^{out}} h_{pst} \sum_{m \in M_{as}} I_{pmst}$</td></tr>
<tr><td>h) Handling costs</td><td></td><td>$\sum_{a \in A} \sum_{p \in P_a^{out}} \sum_{a' \in A_a^{out}} f_{paa'st}^{h} F_{p(s,a)(s,a')t}$</td></tr>
<tr><td>i) Outflow to other sites</td><td colspan="2">$\sum_{a,a' \in A-\{\bar{a}\}} \sum_{p \in P_a^{out} \cap P_{a'}^{in}} \sum_{s' \in N_{ps}^{out}} f_{pss't}^{o} F_{p(s,a)(s',a')t}$</td></tr>
<tr><td>j) Outflow to demand zones</td><td colspan="2">$\sum_{a \in A_{\bar{a}}^{in}} \sum_{p \in P_{\bar{a}}^{in}} \sum_{d \in D_{ps}} f_{psdt}^{o} F_{p(s,a)(d,\bar{a})t}$</td></tr>
<tr><td rowspan="2">Revenues</td><td>k) Outflow to other sites</td><td colspan="2">$\sum_{a,a' \in A-\{\bar{a}\}} \sum_{p \in P_a^{out} \cap P_{a'}^{in}} \sum_{s' \in N_{ps}^{out}} (\bar{\pi}_{pst} + f_{pss't}^{t}) F_{p(s,a)(s',a')t}$</td></tr>
<tr><td>l) Outflow to demand zones</td><td colspan="2">$\sum_{a \in A_{\bar{a}}^{in}} \sum_{p \in P_{\bar{a}}^{in}} \sum_{d \in D_{ps}} \hat{e}_{o(s)o(d)t} \bar{\pi}_{pdt} F_{p(s,a)(d,\bar{a})t}$</td></tr>
</table>

***Table 2*: Facilities Expenses and Revenues in Local Currency for a Given Period and Site**

Lainez *et al*. (2007) proposed a SCN design model for the chemical industry maximizing a corporate value metric, and they show that their approach yields better results than models with profit or NPV maximization objectives. Their work is based on Hugo and Pistikopoulos (2005) who were the first to consider the effects of depreciation, and the salvage value of the SCN. The design model recently proposed by Guillén and Grossman (2009) adopts a similar approach. In the following paragraph, we also adopt a value-based formulation, but we remove some ambiguities by making a clear distinction between accounting depreciation and financial amortization, and we provide a more detailed representation of financial requirements.The purpose of our model is to maximize the value added over a multi-period planning horizon. This can be done by maximizing the corporate value (*CV*) given by:

$$CV = \sum_{t \in T}\left[\frac{FCF_t}{(1+\alpha)^t}\right] + \frac{SVC_{|T|}}{(1+\alpha)^{|T|}} \tag{26}$$

The first term of this objective function is the sum of discounted *free cash flows* (FCF_t) over the planning periods. Recall that α is the cost of capital associated to the WACC. Annual FCF_t are defined as the difference between *net annual earnings* (NAE_t) and *financial requirements* (FR_t) (Yucesan, 2007). The second term is the discounted *salvage value of the company* ($SVC_{|T|}$). It is given by the book value of the fixed assets acquired by the company minus the total depreciation made along the planning horizon (Guillén and Grossman, 2009). It may be seen as the residual value of the total investment made. However, in order not to overestimate the value of the company, the residual value of its debt must also be taken into account. More specifically, at the corporate level, the annual FCF_t and the horizon-end $SVC_{|T|}$ can be defined as follows:

$$FCF_t = \underbrace{\sum_{o \in O} \hat{e}_{0ot}(NOPAT_{ot} + \omega_{ot} Dep_{ot})}_{NAE_t} - \underbrace{\sum_{o \in O} \hat{e}_{0ot}(WCR_{ot} + CapExp_{ot})}_{FR_t}$$

$$SVC_{|T|} = \overbrace{\sum_{o \in O}\sum_{c \in C} \hat{e}_{0ot(c)} FA_{oc}}^{\text{Total investment}} - \overbrace{\sum_{o \in O}\sum_{t \in T} \hat{e}_{0ot} Dep_{ot}}^{\text{Total depreciation}} - \overbrace{\sum_{t \in FH-T} FR_t}^{\text{Net debt}} + SVC^0_{|T|}$$

where:

$NOPAT_{ot}$	=	Net operating profit after tax (NOPAT) in country *o* for year *t*.
Dep_{ot}	=	Annual accounting depreciation of the total fixed assets acquired by the company in country *o* in planning cycles 1,…,*c*(*t*), based on the straight-line depreciation method.
WCR_{ot}	=	Working capital requirements in country *o* for year *t* (interests + inventories + other financials).

$CapExp_{ot}$	=	Capital expenditures in country *o* for year *t* (fixed assets + closing costs).
FA_{oc}	=	Fixed assets in country *o* related to investments made in planning cycle *c*.
$SVC^{0}_{\|T\|}$	=	Residual value at the end of the horizon of the platforms/systems already installed before the optimization (constant).

These variables are explained in more details in the following paragraphs. Note that when the financial horizon of the company (*FH*) is shorter than the planning horizon (*T*) used, the last term of the expression for the horizon-end $SVC_{|T|}$ is dropped. In most practical context, however, we have $T \subset FH$ and there is a net debt at the end of the planning horizon.

As can be seen, NAE_t is based on the NOPAT and the total accounting depreciation used as tax shield for a given country over a fiscal period. However, in the NOPAT calculation, divisions realizing profits need to be distinguished from divisions making losses since there is no income tax to pay on losses. This yield:

$$NOPAT_{ot} = (1-\omega_{ot})M^{+}_{ot} - M^{-}_{ot}, \quad o \in O,\ t \in T$$

Based on the straight line depreciation method, the yearly depreciation is given by:

$$Dep_{ot} = Dep^{0}_{ot} + \sum_{c' \le c(t)} \sum_{l \in L_o} \left[\left(\frac{A^{+}_{lc'}}{EL_l} \right) Y^{+}_{lc'} + \sum_{m \in M_l} \left(\frac{a^{+}_{mc'}}{EL_m} \right) Z^{+}_{mc'} \right], \quad o \in O,\ t \in T$$

where EL_l and EL_m are respectively the length of the economic life of platform *l* and system *m* in planning periods, Dep^{0}_{ot} is the depreciation in year *t* for the platforms and systems in use at the beginning of the planning horizon which have not reached the end of their economic life, and L_o is the set of potential platforms for country $o \in O$, i.e. $L_o = \cup_{s \in S_o} L_s$. Note that Dep^{0}_{ot} is a known constant.

Financial requirements are defined over the planning horizon in terms of capital expenditures (*CapExp*) and working capital requirements (*WCR*). More specifically, we have:

$$\text{Financial requirements} = \underbrace{\text{Fixed assets} + \text{Closing costs}}_{CapExp} + \underbrace{\text{Interests} + \text{Inventories} + \text{Other financials}}_{WCR}$$

Financial requirements cover all strategic investments and the strategic costs generated by such investments, and they are crucial for the welfare and survival of the company. Consequently, they must be supported equitably by the cash flows of the company over its financial horizon. For this reason, we assume that the FR_t's are the same for all the periods $t \in FH$ of the financial horizon, i.e. that:

$$FR_t = FR = \frac{\sum_{o\in O}\sum_{c\in C}\hat{e}_{0ot(c)}FR_{oc}}{|FH|}, \forall t \in FH$$

The financial requirements for country *o* in planning cycle *c* are given by:

$$FR_{oc} = FA_{oc} + CC_{oc} + \sum_{t\in T_c} Inv_{ot} + Int_{oc} + OF_{oc}, o \in O,\ c \in C$$

where:

CC_{oc}	=	Closing costs incurred in country *o* for cycle *c*.
Inv_{ot}	=	Value of the inventory held in country *o* at the end of period *t*.
Int_{oc}	=	Interest charges in country *o* for cycle *c*.
OF_{oc}	=	Other financials (banking charges, contract signatures, real options fees, credit protection fees, currency hedging charges…) incurred in country *o* for cycle *c*. In our context, they are assumed to be a known constant.

Using the decision variables and the cost parameters defined previously we also have:

$$FA_{oc} = \sum_{l\in L_o}(A^{+}_{lc}Y^{+}_{lc} + \sum_{m\in M_l} a^{+}_{mc}Z^{+}_{mc}), o \in O,\ c \in C$$

$$CC_{oc} = \sum_{l\in L_o}(A^{-}_{lc}Y^{-}_{lc} + \sum_{m\in M_l} a^{-}_{mc}Z^{-}_{mc}), o \in O,\ c \in C$$

$$Inv_{ot} = \sum_{s\in S_o}\sum_{p\in P^{stor}} \bar{\pi}_{pst} \sum_{m\in M^{stor}_s} I_{pmst}, o \in O,\ t \in T$$

$$Int_{oc} = \alpha(FA_{oc} + CC_{oc} + \sum_{t\in T_c} Inv_{ot}), o \in O,\ c \in C$$

SCN design model

Based on the previous discussion, the design model proposed to optimize the structure of the multinational company network takes the following form:

$$\max CV = \sum_{t\in T}\left[\frac{FCF_t}{(1+\alpha)^t}\right] + \frac{SVC_{|T|}}{(1+\alpha)^{|T|}} \tag{DM}$$

subject to

- Financial variables definition constraints:

$$FCF_t - NAE_t + FR_t = 0, \quad t \in T \tag{27}$$

$$SVC_{|T|} - \sum_{o\in O}\sum_{c\in C}\hat{e}_{0ot(c)}FA_{oc} + \sum_{o\in O}\sum_{t\in T}\hat{e}_{0ot}Dep_{ot} + \sum_{t\in FH-T} FR_t = 0 \tag{28}$$

$$NAE_t - \sum_{o\in O} e_{0ot}\left[(1-\omega_{ot})M^{+}_{ot} - M^{-}_{ot} + \omega_{ot}Dep_{ot}\right] = 0, \quad t \in T \tag{29}$$

$$Dep_{ot} - \sum_{c' \le c(t)} \sum_{l \in L_o} \left[\left(\frac{A^+_{lc'}}{EL_l} \right) Y^+_{lc'} + \sum_{m \in M_l} \left(\frac{a^+_{mc'}}{EL_m} \right) Z^+_{mc'} \right] = Dep^0_{ot}, \quad o \in O,\ t \in T \tag{30}$$

$$|FH|\, FR_t - \sum_{o \in O} \sum_{c \in C} \hat{e}_{0ot(c)} FR_{oc} = 0, \quad t \in T \tag{31}$$

$$FR_{oc} - (FA_{oc} + CC_{oc} + \sum_{t \in T_c} Inv_{ot} + Int_{oc}) = OF_{oc},\ o \in O,\ c \in C \tag{32}$$

$$FA_{oc} - \sum_{l \in L_o} \left[A^+_{lc} Y^+_{lc} + \sum_{m \in M_l} a^+_{mc} Z^+_{mc} \right] = 0, \quad o \in O, c \in C \tag{33}$$

$$CC_{oc} - \sum_{l \in L_o} \left[A^-_{lc} Y^-_{lc} + \sum_{m \in M_l} a^-_{mc} Z^-_{mc} \right] = 0, \quad o \in O, c \in C \tag{34}$$

$$Inv_{ot} - \sum_{s \in S_o} \sum_{p \in P^{stor}} \overline{\pi}_{pst} \sum_{m \in M^{stor}_s} I_{pmst} = 0, \quad o \in O, t \in T \tag{35}$$

$$Int_{oc} = \alpha (FA_{oc} + CC_{oc} + \sum_{t \in T_c} Inv_{ot}),\ o \in O,\ c \in C \tag{36}$$

- Supply market constraints (1) and (2)
- Sales market constraints (3) and (4)
- Facility platform, space and exclusive systems constraints (5), (6), (7), (8) and (9)
- Optional platforms and systems integrity constraints (10), (11), (12) and (13)
- Production activity flow equilibrium constraints (14) and (15)
- Inventory accounting constraints (16) and (17)
- Order cycle and safety stock accounting constraint (18)
- Storage and production capacity constraints (19), (20), and (21)
- Facilities revenue, expense and margin definitions (22), (23), (24) and (25)
- Non-negativity constraints and binary variable definition constraints

(DM) is a large scale mix-integer program (MIP).

5. Computational Issues, Implementation and Results

Test case and solution method

The case elaborated to test the design model proposed is based on data provided by our pulp and paper industry partners and obtained from public pulp and paper databases. A decision support system, developed using SQL Server 2003, Microsoft Excel 2003, VB.net 2005, Concert 2.0 and CPLEX 11.2, was implemented to validate the model. The application developed is used to generate arcs, flows and capacity options, to compute distances and flow costs, to extend data to the multiple period horizon, etc. When modeling fixed costs, a financing scheme of 8 years with a 6% interest rate is utilized. When generating flows, an 800 miles maximum distance service policy is applied. The planning horizon covers five one year cycles. The characteristics of the case study are summarized in *Table 3*. The activity graph considered is described in *Figure 1*, and the nodes of the network are located in Canada and the United States.

Suppliers	6
Mills	7
Converters (internal and external)	4
Distribution centres	10
Demand nodes	495
Potential platforms	45
Potential systems	240
Raw materials and intermediate products	32
Finished products	11
Activities	14
Recipes	250

***Table 3*: Characteristics of the Case Study**

The model proposed is a large MIP, and when considering a long planning horizon, it becomes difficult to solve with CPLEX. When using CPLEX 11.2 to reach an optimal solution, some instances of our test case required several days of computation on a Pentium Quad-core server with 8GB of Ram. However, for all the test cases solved to optimality, we noted that the optimal solution was found before a 1% gap was reached. Consequently, to reduce computational times, the test problems in this section were solved with a MIP gap optimality tolerance of 1%. Also, in order to decrease computational times further, a number of valid cuts were introduced. The first cut is similar to constraint (5) and it states that, for each cycle, at most one original platform can be opened for a given site:

$$\sum_{l \in L_s^{or}} Y_{lc}^{+} \leq 1, \qquad s \in S, c \in C \tag{C1}$$

The second and third cuts state that if a platform/system is opened at the beginning of cycle *c* then it must be operational during this cycle:

$$Y_{lc}^{+} \leq Y_{lt(c)}, \qquad l \in L, c \in C \tag{C2}$$

$$Z_{mc}^{+} \leq Z_{mt(c)}, \qquad m \in M, c \in C \tag{C3}$$

The two last cuts state that a platform/system cannot be closed at the beginning of a cycle unless it was operational during the preceding period.

$$Y_{lc}^{-} \leq Y_{lt(c)-1}, \qquad l \in L, c \in C \tag{C4}$$

$$Z^{-}_{mc} \leq Z_{mt(c)-1}, \qquad m \in M \ , c \in C \tag{C5}$$

These two measures reduced the computational times by a factor of 10.

Numerical results

A sensitivity analysis was performed over the model parameters with uncertain values in order to evaluate their impact on the solution of the problem. According to Martel et al. (2005), manufacturing costs in the Canadian pulp and paper industry are dominated by the costs of materials (70%), production salaries (16%) and energy (14%). Also, the Canadian pulp and paper industry exports over 85% of its total production, and exchange rates were responsible for a 20% earnings cut in 2005. Consequently, the impact of variations in exchange rates, energy costs, raw material market prices and demand forecasts is examined. *Table 4* presents the parameter values tested. For exchange rates, pessimistic, likely and optimistic scenarios are considered. However, for the other parameters, only 2 alternatives are examined. The combination of all these settings results in 24 different scenarios.

Parameter	***Setting 1***	***Setting 2***	***Setting 3***
Exchange rate	0.8\$CAN/\$US	1.12\$CAN/\$US	1.45\$CAN/\$US
Demand level	Forecast	+20% in sheets demand and -20% in newsprint from the 3rd period	
Energy costs	Current costs	25% increase	
Market prices	Current prices	20% increase in Log and BEP[1] prices	

1) BEP: Bleached Eucalyptus Pulp

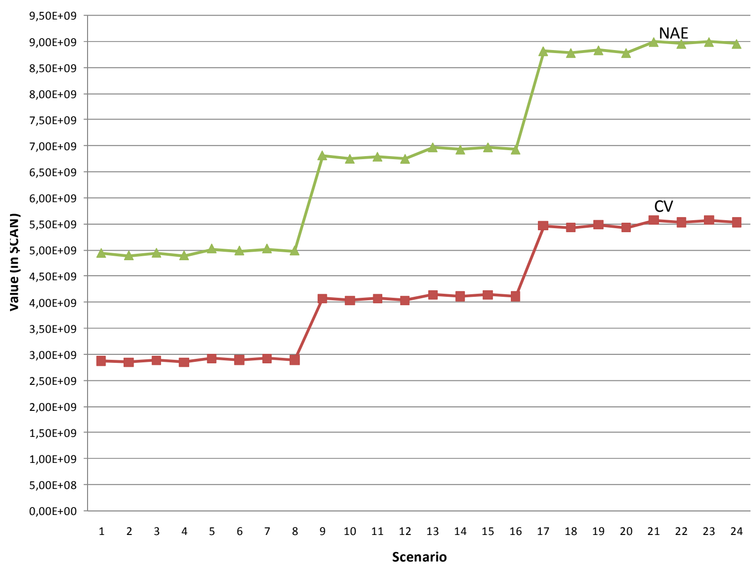
***Table 4*: Parameter Settings for Sensitivity Analysis**

We assumed that the network had to be optimized from scratch, i.e. that no sites were opened at the beginning of the planning horizon. This allows us to study tradeoffs between cash flows, investments and salvage value more easily for this capital intensive industry. Numerical results are presented in *Table 5*. For each scenario considered, the optimal objective function value (*CV*), the total discounted *NAE*, the total *FR* and the discounted *SVC* are given. By plotting *CV* against *NAE* in *Graph 1*, we see at first glance that exchange rate fluctuations have dramatic impacts on the results of the company. Fluctuations in demand forecasts, energy costs and market prices however have little effect on *CV* and *NAE*. On the other end, their impact on *FR* and *SVC* is more pronounced, as can be seen in *Graph 2* and *Graph 3*.

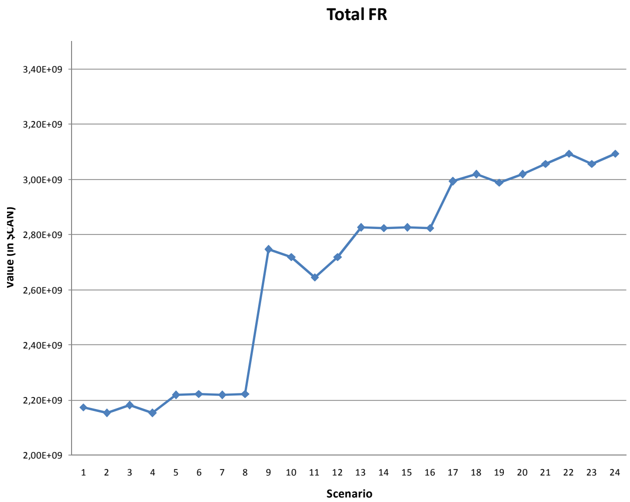
Table 6 presents the number of each type of sites opened in Canada and in the US. As can be seen, the number of opened mills is the same for all scenarios. However, the number of distribution centers (DC) increases when the value of the Canadian dollar decreases. When the Canadian dollar is weak, more warehouses are opened in Canada. On the other end, when the Canadian dollar is strong, an external converter is always used. Most of the sites are opened in the USA, which is to be expected since about 90% of the demand comes from US ship-to-points. Overall, this shows that the network design provided by the model is sensitive to exchange rate fluctuations, but that it is robust with respect to demand and market price fluctuations. These results corroborate those found in Liu and Sahinidis (1995).

Scenario	(ER, D, E, MP)	CV	Total NAE	Total FR	SVC
1	(S1, S1, S1, S1)	2 874 571 159	4 937 361 512	2 172 620 400	277 106 550
2	(S1, S1, S2, S1)	2 848 701 899	4 890 745 115	2 152 253 600	277 068 700
3	(S1, S1, S1, S2)	2 875 873 094	4 941 730 786	2 180 404 400	281 037 550
4	(S1, S1, S2, S2)	2 848 701 899	4 890 745 117	2 152 253 600	277 068 700
5	(S1, S2, S1, S1)	2 921 245 337	5 024 111 275	2 217 254 400	289 393 800
6	(S1, S2, S2, S1)	2 892 068 001	4 985 590 908	2 221 052 400	292 549 550
7	(S1, S2, S1, S2)	2 921 245 337	5 024 111 275	2 217 254 400	289 393 800
8	(S1, S2, S2, S2)	2 892 068 001	4 985 590 908	2 221 052 400	292 549 550
9	(S2, S1, S1, S1)	4 049 846 943	6 817 760 531	2 744 657 280	351 005 304
10	(S2, S1, S2, S1)	4 031 318 413	6 750 304 818	2 718 054 480	348 800 010
11	(S2, S1, S1, S2)	4 064 889 710	6 790 498 339	2 644 049 600	342 680 240
12	(S2, S1, S2, S2)	4 031 277 790	6 749 880 765	2 718 054 480	349 640 010
13	(S2, S2, S1, S1)	4 142 761 464	6 970 652 219	2 824 942 480	356 457 010
14	(S2, S2, S2, S1)	4 111 581 251	6 927 641 004	2 823 895 280	357 269 710
15	(S2, S2, S1, S2)	4 142 761 464	6 970 652 219	2 824 942 480	356 457 010
16	(S2, S2, S2, S2)	4 111 581 251	6 927 641 004	2 823 895 280	357 269 710
17	(S3, S1, S1, S1)	5 461 970 876	8 821 384 134	2 992 140 912	389 617 383
18	(S3, S1, S2, S1)	5 428 704 993	8 786 923 898	3 017 318 840	403 373 550
19	(S3, S1, S1, S2)	5 479 172 892	8 839 532 474	2 987 415 912	388 390 458
20	(S3, S1, S2, S2)	5 428 704 993	8 786 923 901	3 017 318 840	403 373 550
21	(S3, S2, S1, S1)	5 569 180 631	8 998 539 419	3 055 833 912	408 951 258
22	(S3, S2, S2, S1)	5 528 410 437	8 962 016 577	3 093 252 100	416 831 638
23	(S3, S2, S1, S2)	5 569 180 631	8 998 539 419	3 055 833 912	408 951 258
24	(S3, S2, S2, S2)	5 528 410 437	8 962 016 577	3 093 252 100	416 831 638

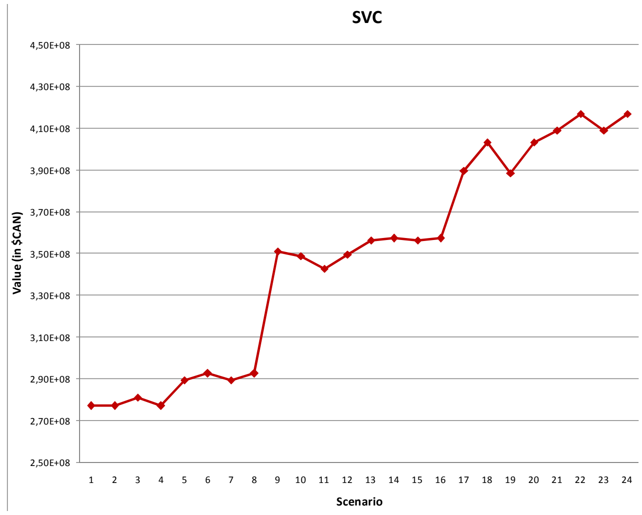
***Table 5*: Numerical Results for the Scenarios Considered**



***Graph 1*: CV and NAE Values for the Scenarios Considered**



***Graph 2*: Impact of Scenarios on Total FR**



***Graph 3*: Impact of Scenarios on SVC**

Scenario	(ER, D, E, MP)	Open mills	Open DCs	Open converters	CAN	USA	TOTAL
1	(S1, S1, S1, S1)	4	5	1	1	9	10
2	(S1, S1, S2, S1)	4	5	1	1	9	10
3	(S1, S1, S1, S2)	4	5	1	1	9	10
4	(S1, S1, S2, S2)	4	5	1	1	9	10
5	(S1, S2, S1, S1)	4	5	1	1	9	10
6	(S1, S2, S2, S1)	4	5	1	1	9	10
7	(S1, S2, S1, S2)	4	5	1	1	9	10
8	(S1, S2, S2, S2)	4	5	1	1	9	10
9	(S2, S1, S1, S1)	4	6		1	9	10
10	(S2, S1, S2, S1)	4	6		1	9	10
11	(S2, S1, S1, S2)	4	6	1	1	10	11
12	(S2, S1, S2, S2)	4	6		1	9	10
13	(S2, S2, S1, S1)	4	6		1	9	10
14	(S2, S2, S2, S1)	4	6		1	9	10
15	(S2, S2, S1, S2)	4	6		1	9	10
16	(S2, S2, S2, S2)	4	6		1	9	10
17	(S3, S1, S1, S1)	4	8		3	9	12
18	(S3, S1, S2, S1)	4	7	1	2	10	12
19	(S3, S1, S1, S2)	4	8		3	9	12
20	(S3, S1, S2, S2)	4	7	1	2	10	12
21	(S3, S2, S1, S1)	4	8		3	9	12
22	(S3, S2, S2, S1)	4	8	1	3	10	13
23	(S3, S2, S1, S2)	4	8		3	9	12
24	(S3, S2, S2, S2)	4	8	1	3	10	13

***Table 6*: Open Sites for the Scenarios Considered**

In order to investigate the importance of considering platform and system options in the design model, even under deterministic demand, we solved a version of the model not including any platform/system options for three typical scenarios. The financial results obtained are given in *Table 7*. As can be seen, for some scenarios, the model including options provides an increase in corporate value (CV) of close to 1%. When no options are available, the SCN designed includes several small focused mills supporting two or three activities. When options are available, however, the SCN designed includes fewer mills, but most of them are larger integrated mills with some system upgrades during the planning horizon. This is illustrated in *Figure 5* for the Windsor

Mill, a facility that is opened in most designs under most scenarios. As can be seen, when options are available, more and larger systems are implemented and, for the pulp production activity, the Kraft and thermo-mechanical pulp system (Kraft & TMS S1) implemented at the beginning of the horizon is upgrader in planning cycle 2 to permit bleaching. The model with options procures more flexibility to accommodate demand and thus it increases the CV of the company, which shows that it is valuable to use a multi-cycle model with platform and system options.

Scenario	CV with no options	CV with options	% CV increase
1	$2 848 579 241	$2 874 571 159	0,91%
9*	$4 049 846 943	$4 071 081 802	0,52%
17*	$5 435 553 787	$5 479 147 663	0,80%

*These problems were solved with a MIP gap optimality tolerance of 0.1%

***Table 7*: CV With and Without Options**

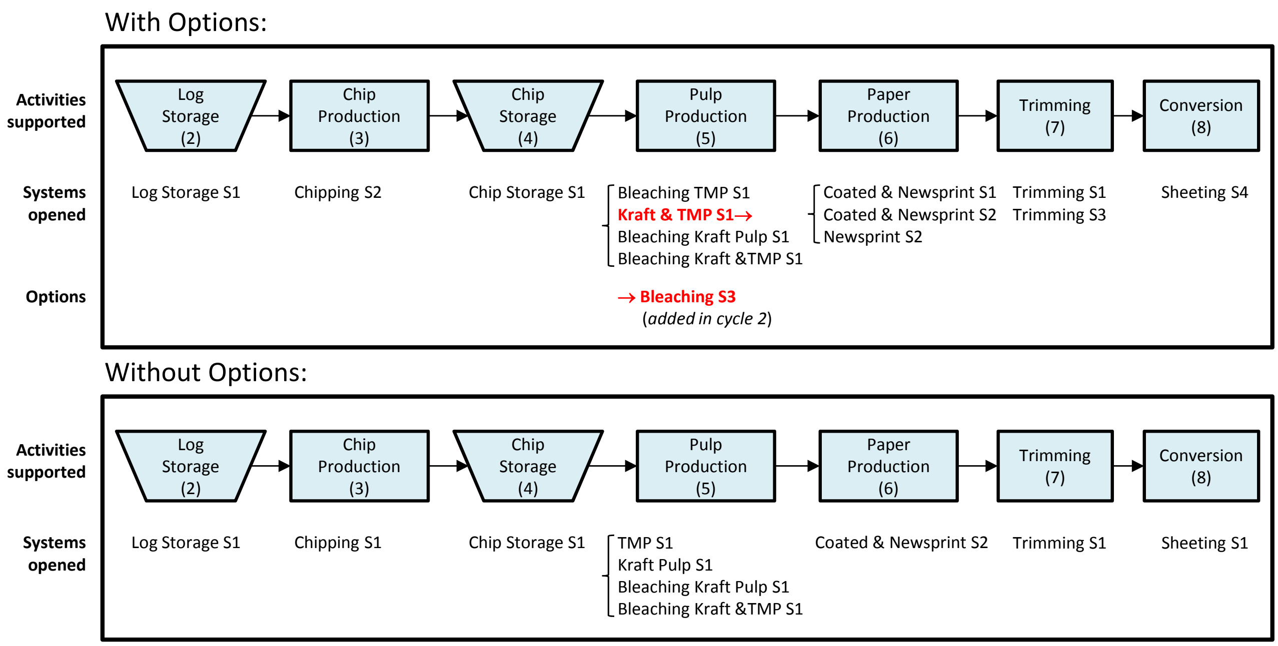
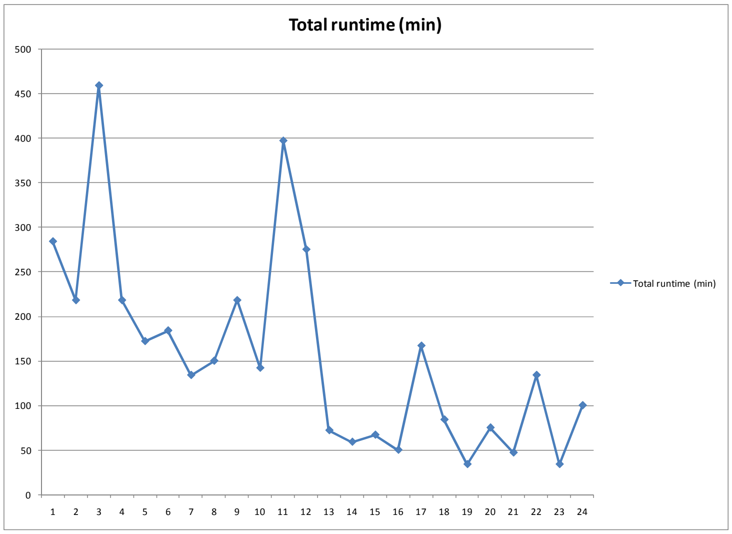


***Figure 5*: Windsor Mill Optimal Design With and Without Options for Scenario 17**

Total runtimes are plotted in *Graph 4*. There is a great difference in runtimes when settings change. Again, exchange rate fluctuations influence total runtimes, especially for scenarios with a strong Canadian dollar. The more difficult problems considered could be solved in less than 8 hours of computational time. The problems solved have a realistic size, mainly when taking into account the fact that we assumed that the whole network could be reengineered. In practice, one would typically optimize only a subset of the network in a reengineering project, and consider that some of the company platforms and systems must be preserved. We experimented with larger versions of the problem including more options and different network structures. In some cases the model obtained could not be solved in a reasonable amount of time. This stresses the fact that the difficulty of solving the type of model proposed in the paper must not be underestimated.



***Graph 4*: Total Runtime (minutes)**

6. Conclusion

This paper proposes a multinational supply chain network design model for the process industry. The model is based on the mapping of a conceptual activity graph, depicting supply chain processes, onto potential platforms and systems associated to production-distribution sites. Its objective is to maximize corporate value added over a planning horizon, based on a performance measurement framework embedding accepted financial, accounting as well as logistic costs measurement concepts. A case study, elaborated from real pulp and paper industry data, is used to validate the model, and a sensitivity analysis is performed to demonstrate its viability over a broad range of business conditions. Our experimental results demonstrate the usefulness of the approach, and they show that exchange rates have a major impact on design decisions and earnings.

The usefulness of the platform and system options concept is also demonstrated, even under deterministic demand. However, in order to select the best real options available, a stochastic version of the model would have to be solved. The model proposed can be easily transformed into a scenario-based two stage stochastic program with recourse, where first cycle design decisions are made here and now and recourse decisions, associated to activity levels and design adjustments, are optimized for each plausible future scenario (Klibi and Martel, 2009). This stochastic model would be huge, but it could be approximated using a sample of scenarios generated using Monte Carlo methods. The resulting sample average approximation (SAA) model would however be much larger than its deterministic version, and heuristic methods would have to be used to spawn near-optimal supply chain network designs.

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