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April 2005

Working Paper DT-2005-AM-1

(Revised March 2006)

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Abstract

This paper presents an optimization methodology to design networks of manufacturing facilities producing several products under deterministic demand. The bill of materials and the operations for each product are taken into account through the use of a product-state graph. Starting from the current state of the manufacturing network, the approach considers a multi-period planning horizon. For each period it specifies the facilities to open within the set of current and potential facilities, the mission for each of the centers in the selected facilities, the equipment to be used for producing the goods, and the structure of the network. Taking human resource competencies into account, the approach selects the type of workers to use for executing the manufacturing tasks. The transfer of resources between plants is also considered. A multi-period mixed integer linear programming model is formulated, a solution method based on the addition of specialized cuts is proposed and computational results are presented.

Keywords

Logistics, Supply Chain Design, Manufacturing Network Design, Location-Allocation, Mixed Integer Programming (MIP)

1. Problem Context

This paper presents an optimization methodology to design manufacturing networks under deterministic demand. In a previous paper, a static network design model including technology selection decisions was proposed (Paquet et al., 2004). The present work extends our previous approach by considering the evolving needs of a network of multiple production center plants over a multi-period planning horizon, and incorporating manufacturing resources (processors and workers) assignment decisions based on their respective capabilities. This kind of decision is critical in many industrial sectors such as semi-conductors, optics-photonics, electronics and telecommunications. Product-state graphs, similar to classical operation process charts, are used to describe the production process of the manufactured products, as illustrated in Figure 1.

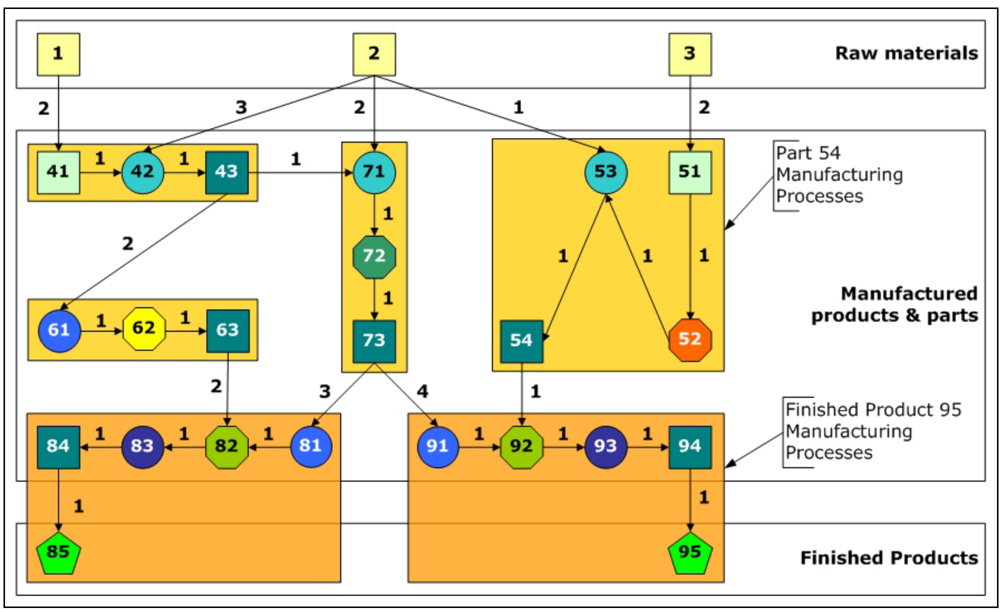

Figure 1: Manufacturing Product-State Graph

This graph can be derived from the bill-of-material (BOM) graph and the sequence of operations required to manufacture each BOM-product, as illustrated in Figure 2. In this figure, products 1, 2 and 3 are raw materials, product-states 43 (read Product 4, Process 3), 54, 63 and 73 are manufactured products, and product-states 85 and 95 are finished products. These end-of-process products can be stored, they can be transferred between production centers in a plant and between plants, and they can be shipped to customers. The other product-states in Figure 1 are intermediate parts which can be transferred between centers, but cannot be stored or shipped between plants. These product-states correspond to manufacturing processes required to build the part. All product-states require various resources to be produced.

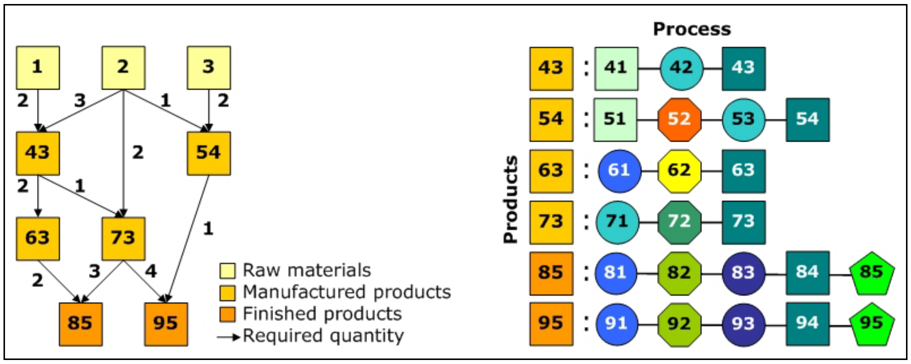

Figure 2: Product Graph & Production Processes

This work is related to several publications in the Supply Chain Design field. Early work on facility location problems with capacity expansion and technology selection is well documented in Verter and Dincer (1992), while Revelle and Laporte (1996) discuss many possible extensions. The modeling advances include concepts like multiple production echelons in the manufacturing network, plant loading, economies of scale and scope, international issues, suppliers selection, outsourcing, etc. Cohen and Moon (1990), Cohen and Moon (1991), Mazzola and Schantz (1997) and Verter and Dasci (2002) take into account economies of scale and scope in their models. Benjaafar and Gupta (1998) and Paquet et al. (2004) discuss technology choice and capacity planning decisions in a manufacturing network. Benjaafar and Sheikhzadeh (2000) discuss the importance of flexible technology at a manufacturing site. The selection of suppliers is also an important issue as discussed in Vonderembse and Tracey (1999). Lakhal et al. (2001) propose a model to determine the activities to outsource. Dogan and Goetschalckx (1999) introduce a multi-season design model. The models proposed by Cohen et al. (1989), Arntzen et al. (1995), Cordeau et al. (2002) and Martel (2005) include many of these critical supply chain design aspects and they are among the most comprehensive models published to date. The evolution of strategic logistic network design models is discussed in Geoffrion and Powers

(1995). Shapiro (2001) also discusses several strategic and tactical supply chain planning issues.

Important weaknesses of current manufacturing network design models are the lack of consideration of manufacturing operations, of the organization of plants into production centers, and of the impact worker competencies may have in some industrial sectors. Also most models in the literature are static: they do not consider evolving production needs, which can be crucial when product life-cycles are relatively short. This paper proposes a design model addressing these issues. The structure of the network, the transfer of resources (processors and workers) between plants, the customer service assignments and the choice of raw material suppliers, over a multi-period planning horizon, are also taken into account by the proposed model. Section 2 presents the model formulation details. Section 3 discusses the solution method, section 4 presents the experimental evaluation of the model and section 5 concludes the paper.

2. Model Formulation

The structure of the manufacturing network considered is illustrated in Figure 3, where only a subset of the demand zones and outbound flows are illustrated. The model considers a set of planning periods which could cover half a year to several years depending on the industry context, and it takes into account the initial state of the network.

Some plants are in use at the beginning of the design process. These plants have resources (processors and workers with different capabilities organized in production centers). Some of these plants can be closed by the model and new plants can be opened on predetermined sites. The configuration of production centers can be adjusted (processor types and required workers). The demand nodes are predetermined and correspond to retailers, warehouses or customer zones. These nodes require finished products and spare parts under a deterministic demand scenario obtained from a set of forecasts based on product life cycle curves. The network operates in a just-in-time or make-to-order manufacturing context and, hence, there is no need to plan for significant inventory storage centers to support customer demand in the network.

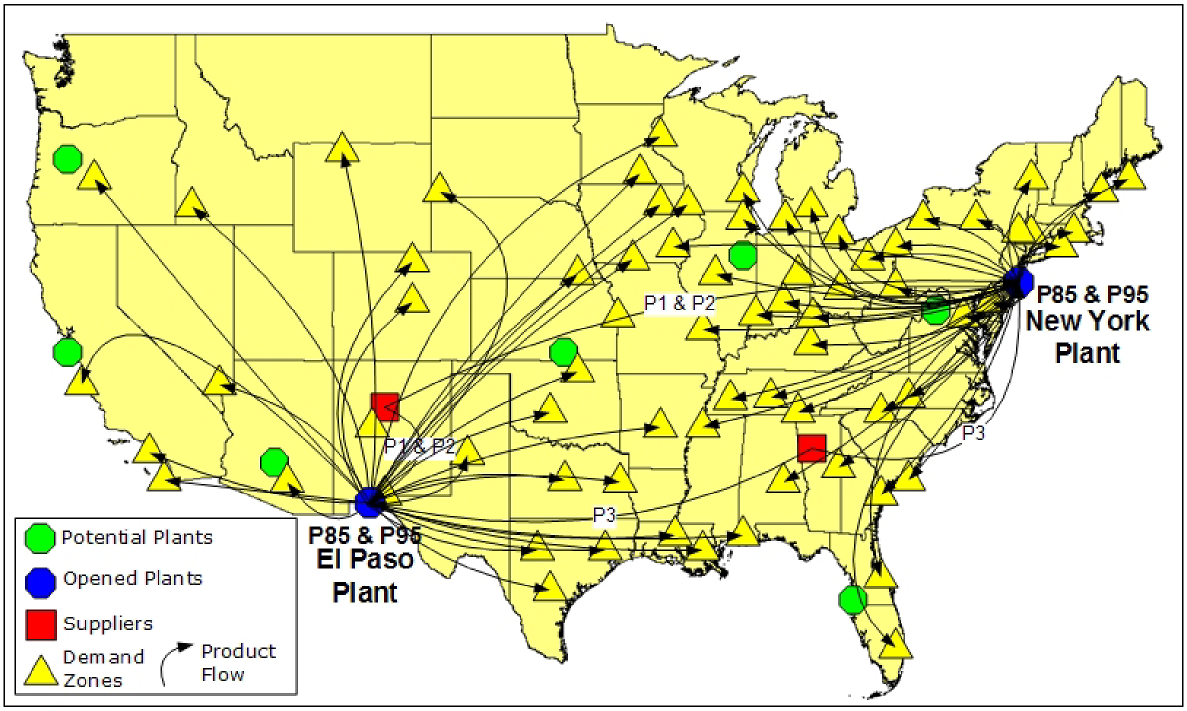

Figure 3: Potential and Current Manufacturing Network for Finished Products P85 & P95

The raw materials come from potential supplier nodes. Limited amounts of each of the raw materials are available from each of the suppliers. The model selects the best supply sources. The manufacturing sites are characterized by a limited space for processors. These processors have a limited capacity and their capabilities are linked to the product-state graph of Figure 1. Specific worker types are required for each product-state on these processors. Human resources are modeled separately of processor resources because they use several processors in their work. The workers taken into consideration in the model are specialists and they may be difficult to find on specific labor markets. They are therefore strategic resources for the firm and their hiring and use must be planned carefully. All workers are flexible within their capability limits. They are not allocated to a specific processor. They can be assigned to any of the different product-states for which they have the required competencies in a specific center.

Resource choices are possible for a given product-state, as illustrated in Figure 4. Substitutions are possible between processors and also between workers. The resources have capabilities, e.g. they can produce a limited set of product-states and they have different processing times and costs. For human resources, highly qualified workers can perform lower level tasks (hierarchy of capabilities), but they cost more then less qualified workers (Vercellis, 1991). The highly qualified workers may also be more difficult to find on specific labor markets. In Figure 4, worker type capability hierarchies are illustrated. In each of these hierarchies, higher number worker types are more qualified than lower number worker types, i.e. in a given hierarchy, a worker type can perform the tasks of preceding worker types. The resources (processors and workers) can be moved from a manufacturing node to another and workers can be laid-off or hired at a specific plant. Overtime can also be used to provide additional capacity during a planning period. It is assumed that the capacity consumption of all resources is linear and that all available time can be used.

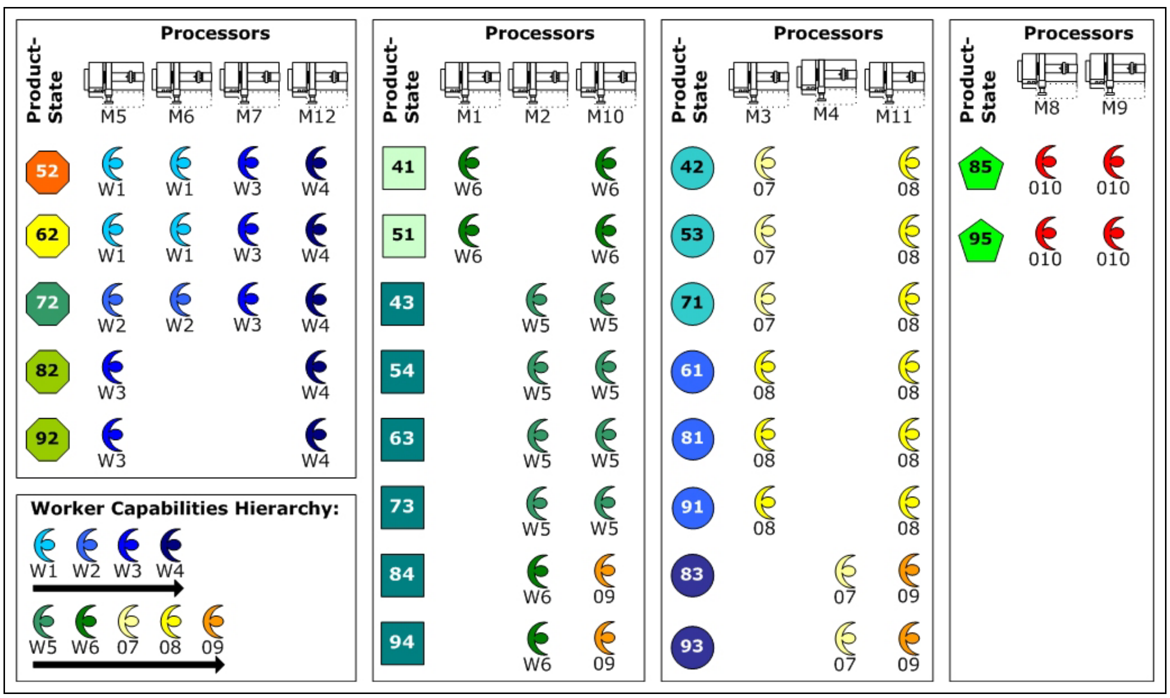

Figure 4: Resource Capabilities

A production center is defined by a specific mission related to the product-states it can produce and the potential resource types it has to produce these product-states. Four types of center are distinguished (see Montreuil and Lefrançois (1996) and Montreuil et al. (1998) for a discussion of center types and missions), as illustrated in Figure 5: *product* centers (grouping of product-states by product, as shown in Figure 1), *function* centers (grouping of product-states by process / shape, as shown in Figure 4), *product group* centers (grouping of two or more products) and *process* centers (grouping of two or more consecutive processes required in more than one product). Each type of center has a unit material handling cost, a total availability (e.g. a work shift) over the planning horizon and a specific efficiency for its resources. This efficiency reflects the extent to which the resources can be used in a particular type of production center. For example, for the manufacturing of a specific product and all its parts, *product* centers are more efficient than the corresponding set of *function* centers because they require less product handling between processors.

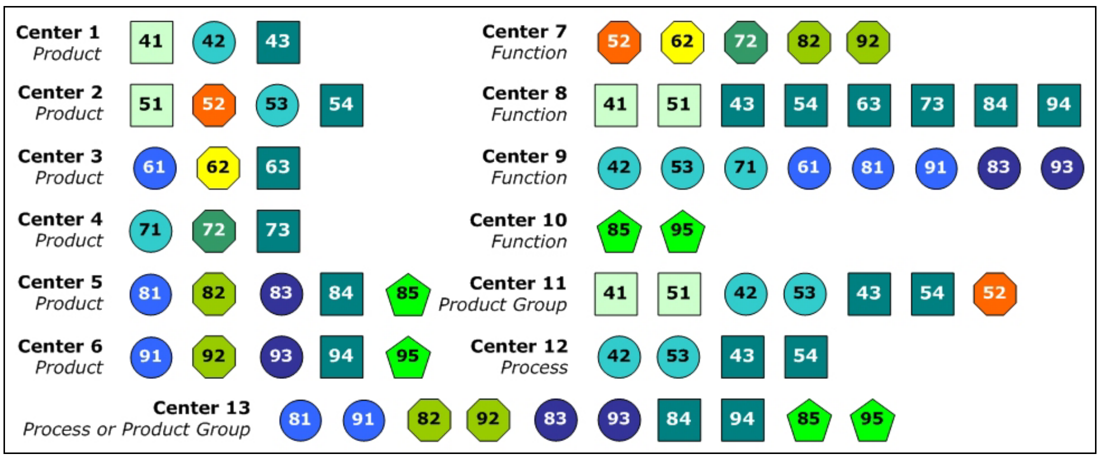

Figure 5: Examples of Potential Production Center with Specific Missions

To formulate the model, the following sets are required:

P:	Nodes of the product-state graph.
$B \subset P$:	Raw materials.
$M \subset P$:	Product-states of manufactured products.
$O \subset M$:	Finished products and spare parts.
R:	Processor types.
$R_u \subset R$:	Potential processor types at plant u ($u \in U$).
$R_{uc} \subset R_u$:	Potential processor types at center c ($c \in C_u$) of plant u ($u \in U$).
$R_p \subset R$:	Processor types which can manufacture product-state p ($p \in M$).
$R_{ucp} \subset R$:	Processor types which can manufacture product-state p ($p \in M$) at center c ($c \in C_u$) of plant u ($u \in U_p$).
W:	Worker types.
$W_u \subset W$:	Potential worker types at plant u ($u \in U$).
$W_{uc} \subset W_u$:	Potential worker types at center c ($c \in C_u$) of plant u ($u \in U$).

$W_{rp} \subset W$:	Worker types which can make product-state p ($p \in M$) on processor type r ($r \in R_p$).
$W_{ucrp} \subset W$:	Worker types which can make product-state p ($p \in M$) on processor type r ($r \in R_p$) at center c ($c \in C_u$) of plant u ($u \in U_p$).
N:	Nodes of the potential manufacturing network.
$V \subset N$:	Potential suppliers.
$V_p \subset V$:	Suppliers which can supply product-state p ($p \in B$).
$U \subset N$:	Potential plants.
$U_t^{+/-} \subset U$:	Plants which can be opened $^{(+)}$ or closed $^{(-)}$ in period t ($t \in T$).
$U_p \subset U$:	Potential plants which can manufacture product-state p ($p \in M$).
$D \subset N$:	Demand zones.
$D_p \subset N$:	Demand zones for product p ($p \in O$).
C:	Potential production centers.
$C_u \subset C$:	Potential centers in plant u ($u \in U$).
$C_p \subset C$:	Centers which can manufacture product-state p ($p \in M$).
$C_{up} \subset C$:	Centers which can manufacture product-state p ($p \in M$) in plant u ($u \in U_p$) $\equiv C_u \cap C_p$.
T:	Periods of the planning horizon.

The indices used for the different sets are:

$p, p' \in P$:	Product-states.
$v \in V$:	Suppliers.
$c \in C$:	Centers.
$u, u' \in U$:	Plants.
$d \in D$:	Demand zones.
$r \in R$:	Processor types.
$w \in W$:	Worker types.
$t \in T$:	Periods.

It is assumed that the product-states are numbered in topological order, i.e. that for each arc (p, p') we have $p' > p$, so that the arcs matrix of the product-states graph is upper-triangular.

The following decision variables are necessary:

F_{vupt}:	Number of units of product-state p ($p \in B$) transported from supplier v ($v \in V_p$) to plant u ($u \in U$) in period t ($t \in T$).

$F_{uu'pt}$: Number of units of product-state p ($p \in M$) transported from plant u ($u \in U_p$) to plant u' ($u' \in U$; $u' \neq u$) in period t ($t \in T$).

F_{udpt} : Number of units of product-state p ($p \in O$) transported from plant u ($u \in U_p$) to demand zone d ($d \in D_p$) in period t ($t \in T$).

G_{ucpt} : Binary variable equal to 1 if center c ($c \in C_{up}$) of plant u ($u \in U_p$) has the mission to manufacture product p ($p \in M$) during period t ($t \in T$), and to 0 otherwise.

H_{ucwt} : Number of workers of type w ($w \in W_{uc}$) required in center c ($c \in C_u$) of plant u ($u \in U$) during period t ($t \in T$).

H^{o}_{ucwt} : Overtime required from workers of type w ($w \in W_{uc}$) in center c ($c \in C_u$) of plant u ($u \in U$) in time units during period t ($t \in T$).

$H^{+/-}_{uwt}$: Number of workers of type w ($w \in W_u$) to hire $^{(+)}$ or lay-off $^{(-)}$ at plant u ($u \in U$) at the beginning of period t ($t \in T$).

$H_{uu'wt}$: Number of workers of type w ($w \in W_u \cap W_{u'}$) to transfer from plant u ($u \in U$) to plant u' ($u' \in U$; $u' \neq u$) at the beginning of period t ($t \in T$).

$\hat{H}_{ucwrpt}$: Time required from workers of type w ($w \in W_{ucrp}$) to produce product p ($p \in M$) at center c ($c \in C_{up}$) of plant u ($u \in U_p$) with processor r ($r \in R_{ucp}$) during period t ($t \in T$).

X_{ucwrpt} : Number of units of product-state p ($p \in M$) manufactured in center c ($c \in C_{up}$) of plant u ($u \in U_p$) with processor r ($r \in R_{ucp}$) by workers of type w ($w \in W_{ucrp}$) in period t ($t \in T$).

Y_{ut} : Binary variable equal to 1 if plant u ($u \in U$) is open during period t ($t \in T$) and to 0 otherwise.

$Y^{+/-}_{ut}$: Binary variable equal to 1 if plant u ($u \in U$) is to be opened $^{(+)}$ ($u \in U^{+}_{t}$) or closed $^{(-)}$ ($u \in U^{-}_{t}$) at the beginning of period t ($t \in T$) and to 0 otherwise.

Z_{ucrt} : Number of processors of type r ($r \in R_{uc}$) required in center c ($c \in C_u$) of plant u ($u \in U$) during period t ($t \in T$).

Z^{o}_{ucrt} : Overtime from processors of type r ($r \in R_{uc}$) required in center c ($c \in C_u$) of plant u ($u \in U$) in time units during period t ($t \in T$).

$Z^{+/-}_{urt}$: Number of processors of type r ($r \in R_u$) to buy $^{(+)}$ or sell $^{(-)}$ at plant u ($u \in U$) at the beginning of period t ($t \in T$).

$Z_{uu'rt}$: Number of processors of type r ($r \in R_u \cap R_{u'}$) to relocate from plant u ($u \in U$) to plant u' ($u' \in U$; $u' \neq u$) at the beginning of period t ($t \in T$). Relocations of processors between centers of a given plant are omitted.

$\hat{Z}_{ucrpt}$: Time on processors of type r ($r \in R_{ucp}$) required to produce product p ($p \in M$) at center c ($c \in C_{up}$) of plant u ($u \in U_p$) during period t ($t \in T$).

The following parameters describe the initial state of the manufacturing network:

H_{ucw0}: Number of workers of type w ($w \in W_{uc}$) initially working in center c ($c \in C_u$) of plant u ($u \in U$).

Y_{u0}: Equal to 1 if plant u ($u \in U$) is initially open and 0 otherwise.

Z_{ucr0}: Number of processors of type r ($r \in R_{uc}$) initially available in center c ($c \in C_u$) of plant u ($u \in U$).

It is assumed that the stakeholders want to find the design which minimizes the sum of state transition costs, fixed costs and variable operating costs over the planning horizon. Without loss of generality, the transition costs and the variable operating costs are assumed to be paid during the planning period in which they are incurred and the fixed costs are assumed to cover real plant and equipment devaluation, opportunity costs and fixed operating costs for the period considered. All costs are expressed in net present value. The model includes the following costs parameters:

a_{ut}^{u}: Fixed cost associated to the use of plant u ($u \in U$) during period t ($t \in T$).

a_{urt}^{r}: Fixed cost associated to the use of a processor of type r ($r \in R_u$) at plant u ($u \in U$) during period t ($t \in T$).

a_{uwt}^{w}: Fixed cost associated to the use of a worker of type w ($w \in W_u$) at plant u ($u \in U$) during period t ($t \in T$).

c_{urt}: Variable cost associated to the use in overtime of a processor of type r ($r \in R_u$) at plant u ($u \in U$) during period t ($t \in T$).

c_{uwt}^{o}: Variable cost associated to the use in overtime of a worker of type w ($w \in W_u$) at plant u ($u \in U$) during period t ($t \in T$).

c_{vupt}^{v}: Unit purchase cost of raw material p ($p \in B$) from supplier v ($v \in V_p$) by plant u ($u \in U$) during period t ($t \in T$).

c_{vupt}^{t}: Unit delivery cost of raw material p ($p \in B$) from supplier v ($v \in V_p$) to plant u ($u \in U$) during period t ($t \in T$).

$c_{uu'pt}^{t}$: Unit transportation cost of product-state p ($p \in M$) from plant u ($u \in U_p$) to plant u' ($u' \in U$) during period t ($t \in T$).

c_{udpt}^{t}: Unit transportation cost of product-state p ($p \in O$) from plant u ($u \in U_p$) to demand zone d ($d \in D_p$) during period t ($t \in T$).

c_{ucpt}^{p}: Unit handling cost of product-state p ($p \in M$) in center c ($c \in C_{up}$) of plant u ($u \in U_p$) during period t ($t \in T$).

$c_{uu'rt}^{r}$: Unit cost of relocating a processor of type r ($r \in R_u \cap R_{u'}$) from plant u ($u \in U$) to plant u' ($u' \in U$) at the beginning of period t ($t \in T$).

$o_{ut}^{u+/-}$: Fixed cost associated to the opening (+) or closing (-) of plant *u* ($u \in U_t^+$; $u \in U_t^-$) at the beginning of period *t* ($t \in T$).

$o_{uwt}^{w+/-}$: Unit cost of hiring (+) or laying-off (-) a worker of type *w* ($w \in W_u$) in plant *u* ($u \in U$) at the beginning of period *t* ($t \in T$).

$c_{uu'wt}^{w}$: Unit cost of transferring a worker of type *w* ($w \in W_u \cap W_{u'}$) from plant *u* ($u \in U$) to plant *u'* ($u' \in U$; $u' \neq u$) at the beginning of period *t* ($t \in T$).

$o_{urt}^{r+/-}$: Unit buying (+) or selling (-) cost of a processor of type *r* ($r \in R_u$) by plant *u* ($u \in U$) at the beginning of period *t* ($t \in T$).

To formulate the model, the following functional parameters are also required:

b_{ucrt}^{r}: Capacity provided in time units by a processor of type *r* ($r \in R_{uc}$) at center *c* ($c \in C_u$) of plant *u* ($u \in U$) during period *t* ($t \in T$).

b_{ucwt}^{w}: Capacity provided in time units by a worker of type *w* ($w \in W_{uc}$) at center *c* ($c \in C_u$) of plant *u* ($u \in U$) during period *t* ($t \in T$).

b_{ucwt}^{o}: Maximum overtime a worker of type *w* ($w \in W_{uc}$) can do at center *c* ($c \in C_u$) of plant *u* ($u \in U$) during period *t* ($t \in T$).

b_{pvt}^{v}: Upper bound on the amount of raw material *p* ($p \in B$) that can be provided by supplier *v* ($v \in V_p$) during period *t* ($t \in T$).

e_r^r: Space required by a processor of type *r* ($r \in R$), including working space and buffer space.

e_u^u: Total space available for processors at site *u* ($u \in U$).

g_{wt}: Upper bound on the number of workers of type *w* ($w \in W$) which can be employed by the company during period *t* ($t \in T$).

$g_{uwt}^{+/-}$: Upper bound on the number of workers of type *w* ($w \in W_u$) which can be hired (+) or laid-off (-) by plant *u* ($u \in U$) at the beginning of period *t* ($t \in T$).

h_{rpt}^{r}: Number of time units of processor of type *r* ($r \in R_p$) required to produce one unit of product-state *p* ($p \in M$) during period *t* ($t \in T$).

h_{rwpt}^{w}: Number of time units of worker of type *w* ($w \in W_{rp}$) required on a processor of type *r* ($r \in R_p$) to manufacture one unit of product-state *p* ($p \in M$) during period *t* ($t \in T$).

$n_{pp'}$: Number of units of product-state *p* ($p \in B \cup M$) required to make one unit of product-state *p'* ($p' \in M$).

x_{pdt}: Number of units of product *p* ($p \in O$) required by demand node *d* ($d \in D_p$) during period *t* ($t \in T$).

Given these sets, parameters, indices and variables, the problem is formally defined by the following mixed-integer programming model. The size of the model, in terms of number of variables and constraints, is given roughly by the following expressions:

- Number of variables: $(|U|\times|P|+3|U|\times|U|+|U|\times|D|+6|C|+|U|+|W|+|R|+|P|)\times|T|$
- Number of binary variables: $(|C|+|U|)\times|T|$ (1)
- Number of constraints: $(|V|+5|U|+9|C|+|D|+|R|+4|W|+3|P|)\times|T|$

Minimize all relevant costs: P_{MIP}

Utilization, Opening, Closing of Plants, and Production:

$$\sum_{u\in U}\sum_{t\in T} a^{u}_{ut} Y_{ut} + \sum_{u\in U^{+}_{t}}\sum_{t\in T} o^{u+}_{ut} Y^{+}_{ut} + \sum_{u\in U^{-}_{t}}\sum_{t\in T} o^{u-}_{ut} Y^{-}_{ut} + \sum_{u\in U_p}\sum_{c\in C_{up}}\sum_{w\in W_{ucrp}}\sum_{r\in R_{ucp}}\sum_{p\in M}\sum_{t\in T} c^{p}_{ucpt} X_{ucwrpt}$$

Utilization, Overtime, Hiring and Laying-Off of Workers:

$$+\sum_{u\in U}\sum_{c\in C_u}\sum_{w\in W_{uc}}\sum_{t\in T}\left(a^{w}_{uwt} H_{ucwt} + c^{o}_{uwt} H^{o}_{ucwt}\right) + \sum_{u\in U}\sum_{w\in W_u}\sum_{t\in T}\left(o^{w+}_{uwt} H^{+}_{uwt} + o^{w-}_{uwt} H^{-}_{uwt}\right)$$

Transfer of Workers and Processors: (2)

$$+\sum_{u\in U}\sum_{u'\in U}\sum_{w\in W_u\cap W_{u'}}\sum_{t\in T} c^{w}_{uu'wt} H_{uu'wt} + \sum_{u\in U}\sum_{u'\in U}\sum_{r\in R_u\cap R_{u'}}\sum_{t\in T} c^{r}_{uu'rt} Z_{uu'rt}$$

Utilization, Overtime, Buying and Selling of Processors:

$$+\sum_{u\in U}\sum_{c\in C_u}\sum_{r\in R_{uc}}\sum_{t\in T}\left(a^{r}_{urt} Z_{ucrt} + c_{urt} Z^{o}_{ucrt}\right) + \sum_{u\in U}\sum_{r\in R_u}\sum_{t\in T}\left(o^{r+}_{urt} Z^{+}_{urt} + o^{r-}_{urt} Z^{-}_{urt}\right)$$

Raw Materials Supply and Transportation of Products:

$$+\sum_{v\in V_p}\sum_{u\in U}\sum_{p\in B}\sum_{t\in T}\left(c^{v}_{vupt} + c^{t}_{vupt}\right) F_{vupt} + \sum_{u\in U_p}\sum_{u'\in U}\sum_{p\in M}\sum_{t\in T} c^{t}_{uu'pt} F_{uu'pt} + \sum_{u\in U_p}\sum_{d\in D_p}\sum_{p\in O}\sum_{t\in T} c^{t}_{udpt} F_{udpt}$$

Subject to:

External Supplier Capacity Constraints:

$$\sum_{u\in U} F_{vupt} \le b^{v}_{pvt} \qquad \forall p\in B, v\in V_p, t\in T \tag{3}$$

Raw Material Requirement Constraints:

$$\sum_{c\in C_{up'}}\sum_{w\in W_{ucrp'}}\sum_{r\in R_{ucp'}}\sum_{p'\in M} n_{pp'} X_{ucwrp't} - \sum_{v\in V_p} F_{vupt} \le 0 \qquad \forall p\in B, u\in U, t\in T \tag{4}$$

Processor Requirement Constraints:

$$\sum_{w\in W_{ucrp}} h^{r}_{rpt} X_{ucwrpt} - \hat{Z}_{ucrpt} = 0 \qquad \forall u\in U_p, c\in C_{up}, r\in R_{ucp}, p\in M, t\in T \tag{5}$$

Processor Capacity Constraints:

$$\sum_{p\in M} \hat{Z}_{ucrpt} - b^{r}_{ucrt} Z_{ucrt} - Z^{o}_{ucrt} \le 0 \qquad \forall u\in U, c\in C_u, r\in R_{uc}, t\in T \tag{6}$$

Worker Time Requirement Constraints:

$$h_{rwpt}^{w} X_{ucwrpt} - \hat{H}_{ucwrpt} = 0 \qquad \forall u \in U_p, c \in C_{up}, w \in W_{ucrp}, r \in R_{ucp}, p \in M, t \in T \tag{7}$$

Worker Capacity Constraints:

$$\sum_{p \in M} \sum_{r \in R_{ucp}} \hat{H}_{ucwrpt} - b_{ucwt}^{w} H_{ucwt} - H_{ucwt}^{o} \le 0 \qquad \forall u \in U, c \in C_u, w \in W_{uc}, t \in T \tag{8}$$

Worker Overtime Limit Constraints:

$$H_{ucwt}^{o} - b_{ucwt}^{o} H_{ucwt} \le 0 \qquad \forall u \in U, c \in C_u, w \in W_{uc}, t \in T \tag{9}$$

Space Floor Constraints:

$$\sum_{c \in C_u} \sum_{r \in R_{uc}} e_r^r Z_{ucrt} - e_u^u Y_{ut} \le 0 \qquad \forall u \in U, t \in T \tag{10}$$

Product Flow Constraints:

$$\begin{aligned}&\sum_{c \in C_{up}} \sum_{w \in W_{ucrp}} \sum_{r \in R_{ucp}} X_{ucwrpt} + \sum_{u' \in U_p} F_{u'upt} - \sum_{u' \in U} F_{uu'pt} - \sum_{d \in D_p} F_{udpt} \\ &- \sum_{c \in C_{up'}} \sum_{w \in W_{ucrp'}} \sum_{r \in R_{ucp'}} \sum_{p' > p \in M} n_{pp'} X_{ucwrp't} \ge 0 \qquad \forall u \in U_p, p \in M, t \in T\end{aligned} \tag{11}$$

Product Demand Constraints:

$$\sum_{u \in U_p} F_{udpt} = x_{pdt} \qquad \forall p \in O, d \in D_p, t \in T \tag{12}$$

Processor Accounting Constraints:

$$\sum_{c \in C_u} Z_{ucrt} + Z_{urt}^{-} - Z_{urt}^{+} + \sum_{u' \in U} Z_{uu'rt} - \sum_{u' \in U} Z_{u'urt} - \sum_{c \in C_u} Z_{ucrt-1} = 0 \qquad \forall u \in U, r \in R_u, t \in T \tag{13}$$

Worker Accounting Constraints:

$$\begin{aligned}&\sum_{c \in C_u} H_{ucwt} + H_{uwt}^{-} - H_{uwt}^{+} + \sum_{u' \in U} H_{uu'wt} - \sum_{u' \in U} H_{u'uwt} \\ &- \sum_{c \in C_u} H_{ucwt-1} = 0 \qquad \forall u \in U, w \in W_u, t \in T\end{aligned} \tag{14}$$

Worker Employment Constraints:

$$H_{uwt}^{+} \le g_{uwt}^{+} \qquad \forall u \in U, w \in W_u, t \in T \tag{15}$$

Worker Lay-off Constraints:

$$H_{uwt}^{-} \le g_{uwt}^{-} \qquad \forall u \in U, w \in W_u, t \in T \tag{16}$$

Global Workforce Size Constraints:

$$\sum_{u \in U} \sum_{c \in C_u} H_{ucwt} \le g_{wt} \qquad \forall w \in W, t \in T \tag{17}$$

Plant State Constraints:

$$Y_{ut} + Y_{ut}^{-} - Y_{ut}^{+} - Y_{ut-1} = 0 \qquad \forall u \in U, t \in T \tag{18}$$

Plant Opening and Closing Constraints:

$$Y_{ut}^{-} + Y_{ut}^{+} <= 1 \qquad \forall u \in U, t \in T \tag{19}$$

Center Mission Constraints (for processors):

$$\sum_{r \in R_{ucp}} \hat{Z}_{ucrpt} - M\left(G_{ucpt}\right) \le 0 \quad \forall u \in U_p, c \in C_{up}, p \in M, t \in T \tag{20}$$

Center Mission Constraints (for workers):

$$\sum_{r \in R_{ucp}} \sum_{w \in W_{ucrp}} \hat{H}_{ucrpt} - M\left(G_{ucpt}\right) \le 0 \quad \forall u \in U_p, c \in C_{up}, p \in M, t \in T \tag{21}$$

Center in Plant Constraints:

$$G_{ucpt} - Y_{ut} \le 0 \quad \forall u \in U_p, c \in C_{up}, p \in M, t \in T \tag{22}$$

Integrality and Non Negativity Constraints:

$$F_{vupt} \ge 0 \quad \forall v \in V_p, u \in U, p \in B, t \in T \tag{23}$$

$$F_{uu'pt} \ge 0 \quad \forall u \in U_p, u' \in U, p \in M, t \in T \tag{24}$$

$$F_{udpt} \ge 0 \quad \forall u \in U_p, d \in D_p, p \in O, t \in T \tag{25}$$

$$X_{ucwrpt} \ge 0 \quad \forall u \in U_p, c \in C_{up}, w \in W_{ucrp}, r \in R_{ucp}, p \in M, t \in T \tag{26}$$

$$H_{ucwt} \ge 0 \text{ integer}; H^{o}_{ucwt} \ge 0 \quad \forall u \in U, c \in C_u, w \in W_{uc}, t \in T \tag{27}$$

$$H^{+}_{uwt} \ge 0; H^{-}_{uwt} \ge 0 \quad \forall u \in U, w \in W_u, t \in T \tag{28}$$

$$H_{uu'wt} \ge 0 \quad \forall u \in U, u' \in U, w \in W_u \cap W_{u'}, t \in T \tag{29}$$

$$\hat{H}_{ucwrpt} \ge 0 \quad \forall u \in U_p, c \in C_{up}, w \in W_{ucrp}, r \in R_{ucp}, p \in M, t \in T \tag{30}$$

$$Z_{ucrt} \ge 0 \text{ integer} \quad \forall u \in U, c \in C_u, r \in R_{uc}, t \in T \tag{31}$$

$$Z^{+}_{urt} \ge 0; Z^{-}_{urt} \ge 0 \quad \forall u \in U, r \in R_u, t \in T \tag{32}$$

$$Z_{uu'rt} \ge 0 \quad \forall u \in U, u' \in U, r \in R_u \cap R_{u'}, t \in T \tag{33}$$

$$\hat{Z}_{ucrpt} \ge 0 \quad \forall u \in U_p, c \in C_{up}, r \in R_{ucp}, p \in M, t \in T \tag{34}$$

$$G_{ucpt} \in \{0,1\} \quad \forall u \in U_p, c \in C_{up}, p \in M, t \in T \tag{35}$$

$$Y_{ut} \in \{0,1\}; Y^{+}_{ut} \ge 0; Y^{-}_{ut} \ge 0 \quad \forall u \in U, t \in T \tag{36}$$

The objective (2) computes all the costs associated with the current network design. Constraints (3) ensure that the capacity of external suppliers is not exceeded. Constraints (4) ensure that the required raw materials are shipped to the plants in the network. Constraints (5) compute the requirement in terms of processors for producing each product. Constraints (6) compute the total requirements for each processor type. Constraints (7) compute worker time requirements for each product. Constraints (8) compute total worker requirements and overtime requirements. Constraints (9) ensure that production in overtime does not exceed the overtime which can be done by the workers. Constraints (10) ensure that the space used in the plants does not exceed its availability. Constraints (11) ensure product flow equilibrium at each node. Constraints (12) are demand satisfaction constraints.

Constraints (13) and (14) ensure that processor and worker movements, acquisitions and disposals are properly accounted for. Constraints (15), (16) and (17) impose restrictions on workforce changes. Constraints (18) and (19) relate the opening and closing of plants to the initial and final site states. Constraints (20) and (21) ensure that work is done only in opened centers and (22) ensure that centers are located only in opened plants. Constraints (23) to (36) are integrality and non-negativity constraints. Capacity constraints for processor resources (5) and (6) and human resources (7) and (8) are modeled in two sets of constraints for better computational efficiency.

It is possible to generalize some of the constraints of the problem. For instance, to make the expansion of the floor space of existing plants possible, constraint (10) can be replaced by constraints (38) and constraints (39) and (40) must be added. These constraints use new continuous variables giving the space required (S_{ut}), the space expansion (S_{ut}^{+}) or reduction (S_{ut}^{-}) and a parameter specifying the space initially available (S_{u0}). Parameter e_u^u of the total plant space is replaced by parameter e_{ut}^u that represents the total space potentially usable at plant *u* in period *t*. The objective function must also be replaced by (37), where c_{ut}^{e+} and c_{ut}^{e-} are respectively the expansion and the reduction costs for plant *u* at period *t*. Constraints (40) are added to compute the required expansion or reduction of the plant space. The formulation is easily altered to account for the case when leasing extra space to outsiders is a potential alternative.

Minimize all costs:

$$(2)+\sum_{u\in U}\sum_{t\in T}\left(c_{ut}^{e+}S_{ut}^{+}+c_{ut}^{e-}S_{ut}^{-}\right) \qquad (37)$$

Required Space Floor Constraints:

$$\sum_{c\in C_u}\sum_{r\in R_u} e_r^r Z_{ucrt} - S_{ut} \le 0 \qquad \forall u\in U, t\in T \qquad (38)$$

Maximum Space Floor Constraints:

$$S_{ut} - e_{ut}^u Y_{ut} \le 0 \qquad \forall u\in U, t\in T \qquad (39)$$

Expansion and Reduction Space Constraints:

$$S_{ut} - S_{ut-1} - S_{ut}^{+} + S_{ut}^{-} = 0 \qquad \forall u\in U, t\in T \qquad (40)$$

To ensure a minimum activity level at a plant, constraints (41) can be added to the formulation. The parameter l_{ut} represents the minimum activity level for the plant *u* in time units in period *t*.

Minimum Plant Activity Level Constraints:

$$\sum_{c\in C_{up}}\sum_{p\in M}\sum_{r\in R_{ucp}}\sum_{w\in W_{ucrp}} h^{w}_{rwpt}X_{ucwrpt} - l_{ut}Y_{ut} \geq 0 \qquad \forall u\in U, t\in T \tag{41}$$

To be more flexible, each plant could use a pool of mobile workers. In this case, some workers are no longer assigned to specific centers in a plant. In order to achieve this type of assignment, the number of mobile workers must be accounted for on a per plant basis, which is done by adding constraint (42). The capacity provided by a mobile worker, b^{m}_{uwt}, is from a plant perspective, as well as the total number of required mobile workers, H^{m}_{uwt}, and the necessary overtime, H^{mo}_{uwt}. These decision variables need to be added in the objective function (2).

Mobile Worker Capacity Constraints:

$$\sum_{c\in C_{u}}\sum_{p\in M}\sum_{r\in R_{ucp}} \hat{H}_{ucwrpt} - \sum_{c\in C_{u}}\left(b^{w}_{ucwt}H_{ucwt} + H^{o}_{ucwt}\right) - b^{m}_{uwt}H^{m}_{uwt} - H^{mo}_{uwt} \leq 0 \tag{42}$$

$$\forall u\in U, w\in W_{uc}, t\in T$$

To take economies of scale and scope into account, processor types with distinct flexibility, capacity and floor space requirements can be used. In extreme cases, it is also possible to replace the processor concept used in this paper by the technology options concept proposed by Paquet et al. (2004). Each of these technology options would correspond to a specified number of processors with associated floor space requirements. Other generalizations may be required for specific situations.

The model can be used to design a new manufacturing network, or to reengineer an existing network, by examining different potential scenarios. These scenarios can be associated to different demand patterns, different service policies, different sets of potential vendors, different sets of potential manufacturing sites, etc. The model could also be used to guide decisions on overtime rules in the context of a labor negotiation, on the introduction of new products, on the opportunity to enter new markets, etc. Finally, it can be used to investigate potential threats, such as the restricted availability of specialized personnel on specific labor markets.

3. Solution Method

With the power of modern commercial solvers, the first solution method to examine is the proprietary branch and bounds algorithm that these solvers implement. Our mixed integer programming (MIP) model can be directly implemented and solved with solvers like CPLEX 9.0 (ILOG, 2003), which was used in our experiments. Commercial solvers can be configured to automatically generate generic cuts to reduce computation times. For example, CPLEX allows the generation of Gomory fractional cuts. Furthermore, our past research (Paquet et al., 2004) showed that specific cuts can be derived to speed up the resolution. The cuts proposed for the model presented here are related to capacity and are defined by equations (43) to (45). A new parameter is required to describe these cuts: the total network requirements for product-state p in period t (x_{pt}). These requirements can be derived from the deterministic demands x_{pdt}. Cuts (43) and (44) calculate the minimum number of processors and workers, respectively, required to satisfy total network demand. Cuts (45) ensures that at least one center is used in the entire network for each manufactured product-states.

Cuts Based on the Minimum Number of Processors:

$$\sum_{u \in U_p} \sum_{c \in C_{up}} \sum_{r \in R_{ucp}} \frac{1}{h^r_{rpt}} \hat{Z}_{ucrpt} \geq x_{pt} \qquad \forall p \in M, t \in T \tag{43}$$

Cuts Based on the Minimum Number of Workers:

$$\sum_{u \in U_p} \sum_{c \in C_{up}} \sum_{r \in R_{ucp}} \sum_{w \in W_{ucrp}} \frac{1}{h^w_{rwpt}} \hat{H}_{ucwrpt} \geq x_{pt} \qquad \forall p \in M, t \in T \tag{44}$$

Cuts Based on the Minimum Number of Centers:

$$\sum_{u \in U_p} \sum_{c \in C_{up}} G_{ucpt} \geq 1 \qquad \forall p \in M, t \in T \tag{45}$$

These conceptually promising accelerative techniques were evaluated, in terms of computational time reduction, through empirical experimentations. In most cases, these techniques, when used with the default parameters of CPLEX, reduce the resolution time slightly. For the experimental evaluations presented in the next section, in order to reduce computational times significantly for all cases, the following branch and bound CPLEX parameter settings are used:

- CPX_PARAM_MIPEMPHASIS is set to CPX_MIPEMPHASIS_HIDDENFEAS, which instructs the solver to search high quality feasible solutions early in the optimization.
- CPX_PARAM_VARSEL is set to CPX_VARSEL_MAXINFEAS, which instructs the solver to branch on variable with maximum infeasibility.
- CPX_PARAM_BRDIR is set to CPX_BRDIR_UP, which instructs the solver to select the up branch first at each node of the branch and bound tree.
- CPX_PARAM_NODESEL is set to CPX_NODESEL_BESTEST, which instructs the solver to select the node with the best estimate of the integer objective value.
- CPX_PARAM_PROBE is set to 3, which is the maximum probing level on variables before branching.

For example, the computational time is decreased from 579 seconds with the *default* settings to 195 seconds with these parameters for Scenario 1 discussed in the next section. In what follows, the use of these CPLEX parameter values is referred to as *optimal settings*. In order to obtain good solutions in an acceptable time for large problems, two additional solver settings were used to reduce the number of branches explored in the branch and bounds solutions tree:

- CPX_PARAM_OBJDIF is set to 500, which instructs the solver to select nodes that have a potential of decreasing the solution by at least 500 $.
- CPX_PARAM_EPGAP is set to 0.03, which instructs the solver to stop the resolution when the best node available has a potential of decreasing the solution by a maximum of 3% of the current best solution.

The problem is not solved to optimality when these parameter values are used and their effect is discussed in the next section. In what follows, the use of these CPLEX parameter values in addition to the *optimal settings* is referred to as *near-optimal settings*. The recent technological progress of commercial solvers enables the efficient solution of more difficult models. It is now possible to tackle realistic problems with commercial solvers and often to solve them more efficiently than with specialized decomposition algorithms when appropriate cuts are used (see Paquet et al. (2004) for a discussion on this topic). It is this solution approach that is tested in this paper.

4. Experimental Evaluation

In this section, we propose a typical use of the model as a decision making tool for helping the managers responsible for the manufacturing network operations. Probable scenarios, for a case based on real life situations in a manufacturing environment, are developed and tested, with an emphasis on the processors and workers used and their organization in production centers. A custom MIP model generator and the ILOG CPLEX Callable Library (ILOG, 2003) are used to solve these scenarios. The MIPs are solved with ILOG CPLEX 9.0 on an AMD Athlon MP 2600+ processor, with 1.00 GB of RAM.

Scenarios 1 to 10 are solved using the optimal settings described earlier. The estimated complexity of this case, as computed with Equation **Erreur ! Source du renvoi introuvable.**, is 5200 variables, 378 binary variables and 3900 constraints. In Scenario 1, the manufacturing network is built from scratch. Table 1 presents the data configuration for this first scenario. In this context, the model can be used as an engineering tool for the design of a completely new network. Potential location for plants, potential center configurations and resources are specified in the model. Different alternatives can be tested with different sets of input data in order to analyze the robustness of the proposed design.

Table 1: Data Configuration of the Scenario 1

Data	Configuration
Periods	T1, T2 & T3 (3 one year periods)
Plants	Potential plants U1 to U4 (Chicago, El Paso, New York & San Francisco)
Centers	C1 to C6 – Produce complete parts only
Products	Finished product-state P85 and all of its parts from the BOM
Processors	Processor types M1 to M8
Workers	Worker types W3, W8 & W10

The optimal solution is found on 195 seconds. In the solution, plant U2 (located in El Paso, TX) is opened and produces all parts for the three periods. Since the demand is increasing, processors and workers are added in the centers during the planning horizon. Table 2 presents the resulting network configuration.

This scenario was modified to test another type of center. In Scenario 2, only function centers are available (e.g. a center for product-states 52, 62, 72, 82 & 92). The optimal solution is found in 21 seconds. The same plant is opened (El Paso, TX), 145 processors are required for period 1 (+13 for period 2 & +18 for period 3) and 148 workers are required at period 1 (+14 for period 2 & +19 for period 3). The total investment for this scenario is 36 769 066 $ (in present value). The resources needed for these two scenarios are equivalent, but with a difference in the overall cost of more than 435 000 $.

Table 2: Optimal Network Configuration Based on Scenario 1

Data		Period 1	Period 2	Period 3
Centers	El Paso C1	Activated	Active	Active
	El Paso C3	Activated	Active	Active
	El Paso C4	Activated	Active	Active
	El Paso C5	Activated	Active	Active
Processors	El Paso M1	17	+1	+2
	El Paso M2	41	+2	+5
	El Paso M3	49	+5	+6
	El Paso M4	5	+1	0
	El Paso M5	7	0	0
	El Paso M6	16	0	+4
	El Paso M7	11	+3	0
	El Paso M8	3	+1	0
	Total	**149**	**+13**	**+17**
Workers	El Paso W3	34	+3	+4
	El Paso W8	109	+8	+15
	El Paso W10	3	+1	0
	Total	**146**	**+12**	**+19**
Total Cost		**36 332 558 $ (in present value) for 3 years**		

The first scenario has also been run with the complete set of developed centers in Scenario 3. The solution is found in 293 seconds at a cost of 36 102 756 $ (in present value). This is a saving of 175 000 $ (compared with Scenario 1). As in the first two scenarios, El Paso, TX, plant is opened. For this scenario, 147 processors are required in period 1 (+12 in period 2 & +17 in period 3) and 144 workers are required for period 1 (+14 for period 2 & +20 for period 3). A combination of product and function centers is selected. Table 3 compares these first three scenarios. These three scenarios show that this formulation can be used to design manufacturing networks by selecting plants and suppliers of raw materials, and by configuring the opened production plants. They also show that the organization of production centers has a significant effect on resource utilization, efficiency and costs.

In Scenario 4 (3645 variables, including 216 binary variables, and 2607 constraints), the addition of a new product (product-state P95) to the current manufacturing network (Scenario 1) is analyzed. The demand forecast for the two finished products is optimistic in this scenario, in particular for the new product P95 which has a very promising demand for periods 2 and 3. The addition of this new product leads to the use of a second plant (Plant 3 – New York, NY) in the third year of the planning horizon. This scenario has a cost of 86 516 107 $ and the optimal solution is found in 144 seconds.

Table 3: Comparison of Scenarios 1, 2 & 3

Data	Scenario 1	Scenario 2	Scenario 3
Plants	Plant U2 (El Paso)	Plant U2 (El Paso)	Plant U2 (El Paso)
Centers	Product centers only	Function centers only	All centers available
Processors	149 + 13 + 17 = 179	145 + 13 + 17 = 175	147 + 12 + 18 = 176
Workers	146 + 12 + 19 = 177	148 + 13 + 18 = 179	144 + 14 + 20 = 178
Costs	36 332 558 $	36 769 066 $	36 102 756 $
Variables	4032 (276 bin. var.)	3672 (276 bin. var.)	5676 (588 bin. var.)
Constraints	2873	2513	4653
Time	195 s.	21 s.	293 s.

In Scenario 5 (5280 variables, including 345 binary variables, and 3487 constraints), a new network is designed to make product P95 by considering a new set of potential plants (five potential plants are used). This new network is completely independent of the network of Scenario 1 in order to emulate a new enterprise. The solution leads to the opening of a plant in Portland, OR. This plant is sufficient in space for the three years of the planning horizon. This scenario has a cost of 49 404 443 $ and the solution is found in 185 seconds.

A new network for products P85 & P95 is build from scratch in Scenario 6 (16183 variables, including 1269 binary variables, and 9075 constraints). The complete sets of plants and centers are used. Since we already know a solution for a subset of this problem from Scenario 4, we use this information as MIP starts values in CPLEX to speed up the resolution of this problem. This scenario has a cost of 87 702 458 $ and the solution is found in 620 seconds with the help of the starting solution. Without this technique, the solution is found in 780 seconds.

The next three scenarios analyze resource capabilities (processors and workers). In these scenarios, the manufacturing network obtained for Scenario 4 is used as the starting network. A base scenario with no modification is built in order to obtain a comparison point for these evaluations, over a three year planning horizon. For Scenario 7, a new flexible processor (M11) is available on the market. The solution leads to a replacement of the processors M3 by this new processor type. A saving of more than 5 000 000 $ over three years can be achieved by using this new type of processor with the current capabilities of the workers. For Scenario 8, a new flexible processor (M12) is available on the market, but this time, new competencies are required for the workers to use it. If the enterprise wants to use this processor type, workers of type W4 are also required. During the planning horizon, processors of type M6 are replaced by processors of type M12 and workers of type W3 are replaced by workers of type W4. This configuration leads to a saving of more than 5 500 000 $ over three years. For Scenario 9, the data of Scenario 8 is used as input, but flexible workers W4 have limited availability. In this case, the cost related to this lack of availability is 2 800 000 $ over three years (compared with Scenario 8). Table 4 shows the comparison of these three scenarios related to the base scenario built from the resulting manufacturing network of Scenario 4.

Table 4: Comparison of Scenarios 7, 8 & 9

Data	Base (Scenario 4)	Scenario 7	Scenario 8	Scenario 9
Processors	M1 to M8	+M11	+M12	+M12
Workers	W3, W8, W10	–	+W4	+W4 (limited)
Costs	133,118,610 $	127,280,403 $	127,548,771 $	130,141,467 $
Variables	2280 (135 bin.)	2442 (135 bin.)	2598 (135 bin.)	2598 (135 bin.)
Constraints	1950	2034	2049	2142
Time	3 s.	102 s.	54 s.	114 s.

Scenario 10 (3645 variables, including 216 binary variables, and 2469 constraints) is built from Scenarios 1 (current network for product P85) and 5 (acquired network for product P95), which emulate the acquisition of a plant and a reconfiguration of the current manufacturing network. Initially, each plant produces one finished product. For this solution, each plant produces all finished products in the last period of the planning horizon. This new configuration requires the rationalization of the resources during the planning horizon (buy, sell, hire, layoff and transfer). At the end of the planning horizon the second plant produces a main product-state (P43) for all plants and one or two finished products for 35% of the clients. The complete solution costs is 107 891 842 $ and the solution is found in 231 seconds (a saving of about 500 000 $ if Scenarios 1 & 5 are run independently with the same demand). Table 5 presents the details of the solution. The values between brackets represent resources transferred from (–) or to (+) a specific plant.

Table 5: Details of the Solution of Scenario 10

Period	Plant U2 (El Paso, TX)			Plant U6 (Portland, OR)		
	Products	Processors	Workers	Products	Processors	Workers
0	43, 63, 73, 85 & 95	179	177	43, 54, 73 & 95	334	328
1	43, 54, 63, 73, 85 & 95	427 [+246 (U6)]	423	43, 54, 73 & 95	66 [–246 (U2)]	63
2	43, 54, 63, 73, 85 & 95	433 [+6 (U6)]	426	43, 73, 85 & 95	76 [–6 (U2)]	66
3	43, 54, 63, 73, 85 & 95	434 [+3 (U6)]	430	43, 73, 85 & 95	74 [–3 (U2)]	68

Scenarios 11 to 25 were elaborated to test the model solution times for real size problems. These scenarios were randomly generated using the data presented in Table 6. Each scenario is generated with realistic data intervals for the customer demands of each period of the planning horizon, and with the same initial state.

Table 6: Data Configuration of the Scenarios 11 to 25

Data	Configuration
Periods	3 one year periods
Suppliers	30 potential suppliers
Plants	10 potential plants
Centers	30 potential centers for all plants (product centers, function centers, process centers & product group centers)
Demand Zones	189 demand zones corresponding to geographically aggregated customers locations
Products	6 finished product families and all of their parts (94 product-states)
Processors	54 processor types
Workers	38 worker types

The problem size for these cases, as estimated with Equation **Erreur ! Source du renvoi introuvable.**, is 14058 variables, 930 binary variables and 10395 constraints. The exact size of the problem generated is comprised between 14961 and 32559 continuous variables, 789 and 1398 binary variables and 11184 and 20967 constraints. The models to solve for these scenarios are up to 10 time larger than for scenarios 1 to 10 (at least 3 times according to the estimations of Equation **Erreur ! Source du renvoi introuvable.**). The near-optimal settings were used to solve these ploblems. The potential network for these scenarios is illustrated in Figure 6.

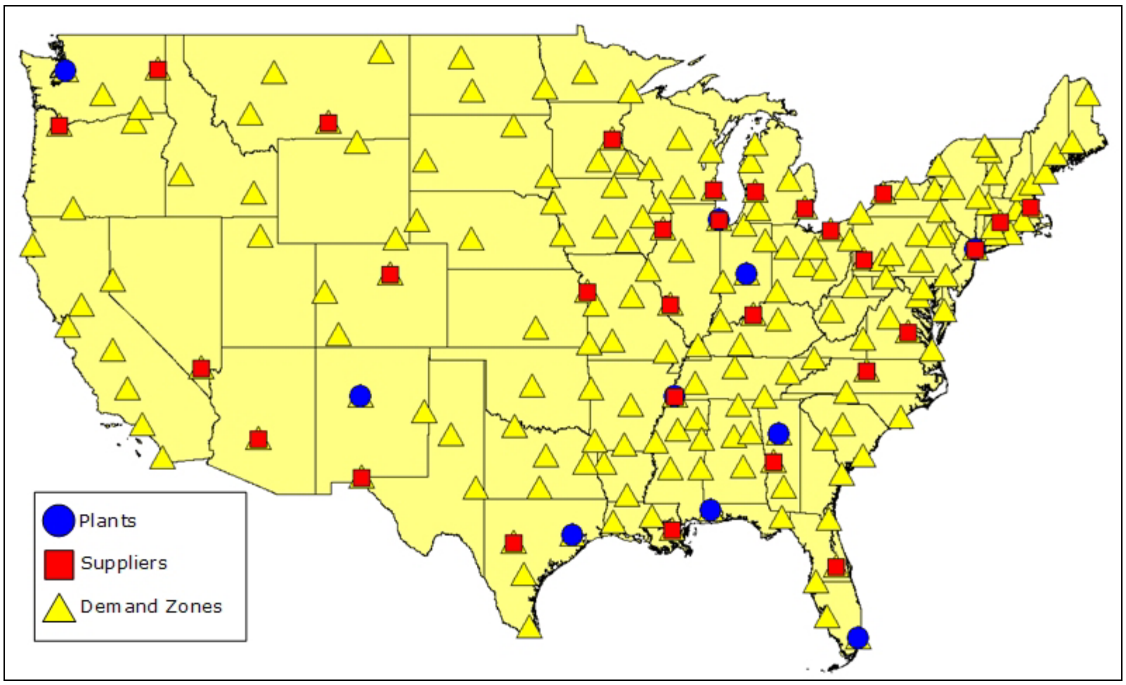

Figure 6: Potential Network for Scenarios 11 to 25

Figure 7 presents an example of solution quality and solution time for near-optimal, optimal and default settings of the solver for Scenario 11. The problem to solve for this scenario is composed of 26265 variables (1134 binary variables) and 15093 constraints. The customized cuts permit to solve the linear relaxation of the problem in 9 seconds compared of 18 seconds without the cuts. Since all nodes evaluated are solved faster, the solution procedure is also faster. Note also that the starting lower bound with the customized cut is higher by 1 690 000 \$, which help for the proof of optimality. The optimal solution is found with the customized parameter settings in more than 15000 seconds. The default parameter solution was stopped after 12 hours of computation with a current solution higher than the optimal cost by more than 2 600 000 $. The near-optimal solution obtained in 874 seconds is less than 32 000 $ (0.03%) higher than the optimal solution. Actually, it takes intensive computational efforts to prove that the near-optimal solution is near the optimal cost. For these 15 scenarios, the solution time is between 454 and 3692 seconds and their solution quality is comprised between 0.01% and 0.81% of the optimal cost.

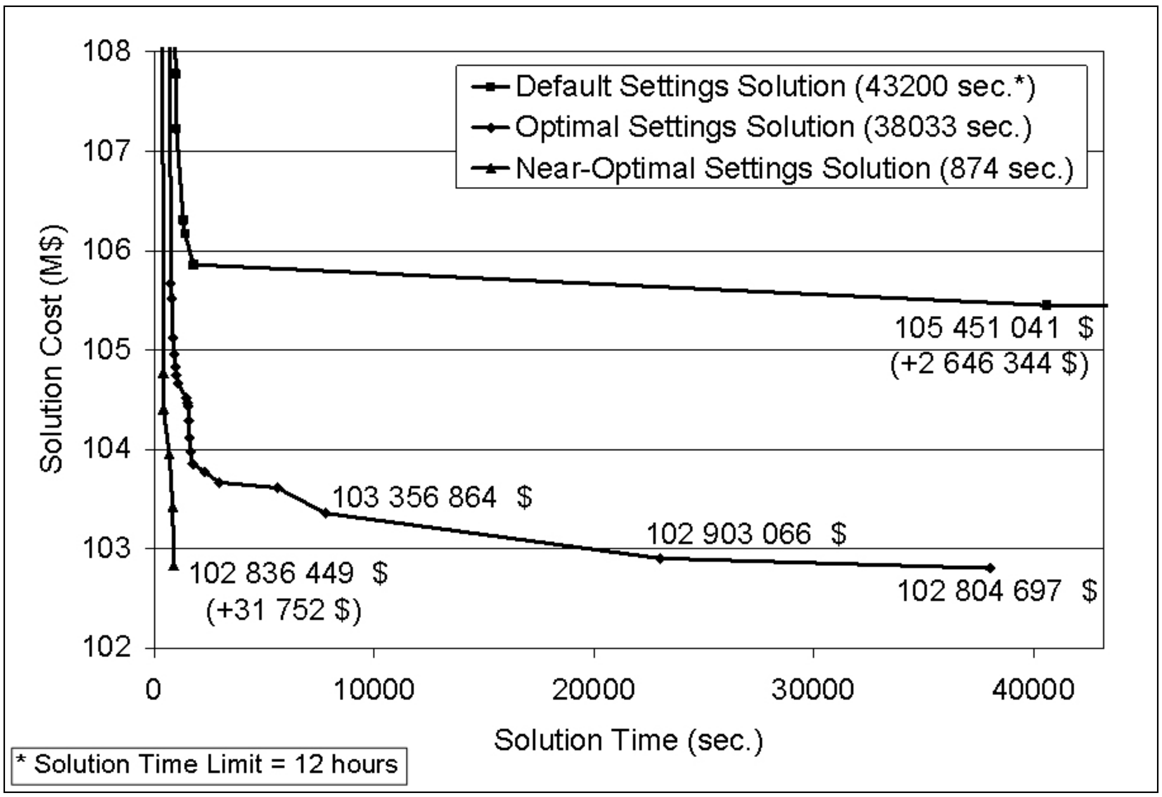

Figure 7: Example of Solution Quality as a Function of Computational Time for Scenario 11

The 25 scenarios tested demonstrate the usefulness of the model as a design and what-if analysis tool for the planning of a manufacturing network with explicit consideration of resources. Some of these scenarios are difficult to solve to optimality with the solver default settings. In fact, the optimal solution is often found after a short amount of time. However, it takes a lot more time to prove that it is optimal, as shown in Figure 7. In order to reduce this time, a better lower bound must be found for the problem. To achieve this, custom cuts have been developed and customized solver settings were used. It is also possible to reduce the solution time by finding a better upper bound, that is, a good start-up solution, using information obtained from previous scenarios (see Scenario 6 for an example).

5. Conclusion

This paper has introduced a multi-period optimization model and a methodology to design networks of manufacturing facilities producing several products under deterministic demand. The approach can deal with the manufacturing operations required for each product, as well as the availability and mobility of manufacturing resources, in multiple production center plants. The operations for each product are taken into account by incorporating product-state graphs in the model. Worker competencies, overtime and processor flexibility are also taken into account. Computational results show that the proposed model can be solved efficiently with commercial mixed-integer programming solvers by adding appropriate cuts to the original model. Future work related to this problem concerns the integration of the order-to-delivery time and the service level in the methodology of manufacturing network design. These factors must be taken into account in order to capture the variation of the demand and its effect on the capacity required.

6. References

Arntzen, B.C., G.G. Brown, T.P. Harrison and L.L. Trafton (1995) Global Supply Chain Management at Digital Equipment Corporation. *Interfaces* **25**(1), 69-93.

Benjaafar, S. and D. Gupta (1998) Scope Versus Focus: Issues of Flexibility, Capacity, and Number of Production Facilities. *IIE Transactions* **30**(5), 413-425.

Benjaafar, S. and M. Sheikhzadeh (2000) Design of Flexible Plant Layouts. *IIE Transactions* **32**(4), 309-322.

Cohen, M.A., M. Fisher and R. Jaikumar (1989) International Manufacturing and Distribution Networks: A Normative Model Framework. In: *Managing International Manufacturing*, Kasra Ferdows (ed), 67-93, Amsterdam: Elsevier Science Publishers.

Cohen, M.A. and S. Moon (1991) An Integrated Plant Loading Model with Economies of Scale and Scope. *European Journal of Operational Research* **50**(3), 266-279.

Cohen, M.A. and S. Moon (1990) Impact of Production Scale Economies, Manufacturing Complexity, and Transportation Costs on Supply Chain Facility Networks. *Journal of Manufacturing and Operation Management* **3**, 269-292.

Cordeau, J.-F., F. Pasin and M.M. Solomon (2002) An Integrated Model for Logistics Network Design. *Les Cahiers du GERAD* **G–2002–07**, 30 p.

Dogan, K. and M. Goetschalckx (1999) A Primal Decomposition Method for the Integrated Design of Multi-Period Production-Distribution Systems. *IIE Transactions* **31**(11), 1027-1036.

Geoffrion, A.M. and R.F. Powers (1995) Twenty Years of Strategic Distribution System Design: An Evolutionary Perspective. *Interfaces* **25**(5), 105-127.

ILOG (2003) ILOG CPLEX 9.0 User's Manual.

Lakhal, S., A. Martel, O. Kettani and M. Oral (2001) On the Optimization of Supply Chain Networking Decisions. *European Journal of Operational Research* **129**(2), 259-270.

Martel, A. (2005) The Design of Production-Distribution Networks: A Mathematical Programming Approach. In: *Supply Chain Optimization*, Geunes, J. and Pardalos, P. (eds), Kluwer Academic Publishers.

Mazzola, J. and R. Schantz (1997) Multiple-Facility Loading Under Capacity-Based Economies of Scope. *Naval Research Logistics* **44**, 229-256.

Montreuil, B. and P. Lefrançois (1996) Organizing Factories as Responsability Networks. In: *Progress in Material Handling Research: 1996*, Robert Graves et al. (eds), 36 p., Ann Arbor, Michigan, U.S.A.: Material Handling Institute, Braum-Brumfield inc.

Montreuil, B., Y. Thibault and M. Paquet (1998) Dynamic Network Factory Planning and Design. In: *Progress in Material Handling Research: 1998*, Robert Graves et al. (eds), 353-380, Ann Arbor, Michigan, U.S.A.: Material Handling Institute, Braum-Brumfield inc.

Paquet, M., A. Martel and G. Desaulniers (2004) Including Technology Selection Decisions in Manufacturing Network Design Models. *International Journal of Computer Integrated Manufacturing* **17**(2), 117-125.

Revelle, C.S. and G. Laporte (1996) The Plant Location Problem: New Models and Research Prospects. *Operations Research* **44**(6), 864-874.

Shapiro, J.F. (2001) Modeling The Supply Chain. 586 p. Duxbury.

Vercellis, C. (1991) Multi-Criteria Models for Capacity Analysis and Aggregate Planning in Manufacturing Systems. *International Journal of Production Economics* **23**(1-3), 261-272.

Verter, V. and A. Dasci (2002) The Plant Location and Flexible Technology Acquisition Problem . *European Journal of Operational Research* **136**(2), 366-382.

Verter, V. and M.C. Dincer (1992) An Integrated Evaluation of Facility Location, Capacity Acquisition, and Technology Selection for Designing Global Manufacturing Strategies. *European Journal of Operational Research* **60**(1), 1-18.

Vonderembse, M.A. and M. Tracey (1999) The Impact of Supplier Selection Criteria and Supplier Involvement on Manufacturing Performance. *Journal of Supply Chain Management* **35**(3), 33-39.