

# **Strategic, Tactical and Operational Decisions in Multi-national Logistics Networks: A Review and Discussion of Modeling Issues**

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May 25, 1999

Revised: August 25, 1999

**Accepted for publication on September 8, 1999  
by the *International Journal of Production Research***

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## **ABSTRACT**

The rapidly developing, world-wide marketplace is leading to the geographical dispersion of production, assembly and distribution operations. This paper deals with three aspects of international logistics networks: strategic, tactical and operational. The strategic level designs the logistics network, including prescribing facility locations, production technologies and plant capacities. The tactical level prescribes material flow management policies, including production levels at all plants, assembly policy, inventory levels, and lot sizes. The operational level schedules operations to assure in-time delivery of final products to customers. This paper reviews the literature that deals with strategic, tactical and operational levels and discusses relevant modeling issues.

## **ACKNOWLEDGEMENTS**

This material is based, in part, upon work supported by the National Science Foundation on Grant DMI-9500211. The authors appreciate the insightful comments offered by Professor Sila Cetinkaya in our discussions. The authors are also indebted to three anonymous referees whose comments allowed us to strengthen an earlier version of this paper.

The rapidly developing, world-wide marketplace has spawned a new allure for the multi-national company to seek out attractive labor markets to reduce cost, locate close to customers to improve customer service, and build new markets in developing countries to enhance profits. For example, the recent NAFTA agreement has led U.S.-based companies to locate assembly plants in Mexico. Companies in Western Europe have begun to establish similar networks to serve the evolving free markets in Eastern Europe. However, to be profitable, the multi-national company must deal with a variety of issues. Companies must consider a number of trade-offs; for example, centralized manufacturing (i.e., production and assembly) to achieve economies of scale versus decentralized operations that seek to improve customer service by locating assembly plants closer to customers. However, achieving a favorable trade-off may not be straight-forward since costs depend upon the countries in which plants are located. For example, the unit cost to produce/assemble depends upon the labor market in each country. The political environment in a country determines tariffs and may place unique constraints on operations. Shipments from one country to another incur border-crossing costs, which may include losses due to monetary exchange rates and to requirements such as the need to transfer materials to a different carrier. Investment costs may also be related to individual countries, since each may be willing to offer unique financial inducements to attract new businesses. Risks must be considered relative to potential profits. A variety of risks face the multi-national company, including the valuation of currency and the political stability of the countries in which it does business.

Management of multi-national companies involves decisions at strategic, tactical and operational levels and relates to multi-product, multi-plant logistics systems, which entail production, assembly, and distribution. The purpose of this paper is to review the literature that deals with strategic, tactical and operational decisions and to discuss relevant modeling issues. Our goal is to foster insight into issues relevant to global logistics networks and encourage the development of algorithms that can solve actual, large-scale problems.

We emphasize that one primary modeling issue is that some aspects of global logistics are difficult – if not impossible – to represent in a mathematical model (see also Vidal and Goetschalckx (1996)). For example, political stability and the rate at which a developing market will mature may be difficult to quantify.

Thus, the scope of this paper is limited to issues that appear to be quantifiable.

The strategic level prescribes a set of locations where facilities are to be located (i.e., “opened”), production technologies to be employed at each facility, and the capacity of each plant. Strategic decisions thus determine the network through which production, assembly and distribution serve the marketplace. Any model applicable to the strategic level must provide manufacturing capacity to satisfy forecast demand for all products and observe precedence relationships among assembly tasks. The objective is to maximize total profit, including the fixed cost of investment to open facilities and the variable cost of manufacturing and distribution, including “border crossing fees” that might be incurred in transit. We define border crossing fees to include all costs associated with moving materials from one country to the next, including tariffs and monetary exchange rates. The strategic level establishes the design of the logistics network and thereby provides the environment in which tactical and operational levels must perform.

The tactical level prescribes material flow management policies, including production levels at all plants, assembly policy, inventory levels, and lot sizes. For instance, should finished products be assembled in large lots and held in centralized warehouses, each of which distributes to a large geographical region, or should final assembly be performed at numerous locations only on demand? The assembly policy impacts customer service through the time required to service demand. Thus, it is important to determine a measure of customer service that can be expected to result at the tactical level and provide this as feedback to the strategic level in order to improve customer service by providing a more responsive network design.

Some issues such as product design may affect both strategic and tactical decisions. For example, changing the design of a product to modular form may require a new logistics network to be designed at the strategic level as well as new material management policies at the tactical level because a modularized product can be assembled at different locations and customized in order to satisfy unique customer demands.

The operational level schedules operations to assure in-time delivery of final products to customers, coordinating the logistics network to be responsive to customer demands. In particular, this paper proposes a scheduling objective of minimizing the throughput time to best serve customers. The associated scheduling problems must consider the due dates of orders, which must be met in a multi-stage environment. Due dates

might be set either internally or externally. Tactical decisions limit the potential locations for carrying out production and assembly tasks by positioning inventories. Components or subassemblies must be transported between geographically dispersed sites, incurring cost and requiring time. The question at the operational level is when to perform a manufacturing task and at which facility so that due dates are met to the fullest extent possible. The operational level must deal with the environment created by decisions made at the tactical level, including the availability of components (i.e., parts) and any resulting bottleneck facilities, which may induce long throughput times, causing due dates to be violated.

The strategic level may deal with a relatively long planning horizon of, say, two to five years since long lead times are required to construct plants and install processing equipment. A relatively high level of uncertainty may be associated with demand, political environments, and exchange rates over such a long planning horizon. The lead time to implement decisions may be shortened by purchasing or leasing existing facilities or by composing a virtual network by subcontracting other companies. Thus, time frames may not distinguish decision levels so much as the type of decisions each entails. It can be expected that shorter planning horizons entail less uncertainty. The tactical level prescribes material flow management policies but is limited by the network made available by strategic-level decisions. In turn, the operational level is limited by tactical-level decisions, which, for example, may position inventories in anticipation of forecast demand. The tactical level deals with a mid-range horizon of, say, 6 - 24 months, forming a bridge between strategic and operational levels. A model for the operational level should be invoked daily to schedule operations relative to current information about jobs in process and the status of each.

Global logistics networks differ from domestic systems in a number of qualitative and quantitative ways. Both must deal with economic factors such as interest rates, market prices, production costs, and transportation costs, but specific values may be country-dependent and, therefore, more difficult to predict on a global scale. Establishing the global logistics network is not merely a matter of seeking out the most favorable labor rates. The global network must be designed and operated to recognize – if not exploit - import tariffs, export taxes, different income tax rates and duties, duty drawbacks, and transfer prices (e.g., Alles and Datar (1998)). The transfer price for a product, the price that the selling “node” in a logistics

network charges the purchasing “node,” is a significant determinant of taxes that a company must pay. The global network must also reckon with political conditions, which also differ by country, and may give rise to trade barriers and government regulations such as local content rules, which require that specified contributed value be added within a country. The governments of different countries may offer widely varying inducements (e.g., tax abatements) to attract new businesses. The location of production and distribution facilities relative to both suppliers and customers is important to achieving a superior service level and determines the economies of scale that might be exploited as a competitive strength. Qualitative factors such as political stability and general infrastructure are difficult to include in mathematical models but may be crucial to global networks. A number of uncertainties affect the level of risk associated with global logistics networks. In particular, uncertainties in demand and exchange rates may predominate, although uncertainty of lead times, supplier reliabilities, and other parameters may also be of concern .

International logistics networks have become familiar in such markets as automobiles, garments and computers. To develop further insight into relevant issues, we describe two companies that are engaged in multi-plant, multi-product, multi-country logistics.

The Compaq Computer Company purchases electronic components from suppliers around the world and assembles circuit cards and personal computers at a number of locations around the world (e.g., Houston, Texas; Scotland; Brazil; Singapore; and China). Recently, the company decided to change its assembly policy with the goal of improving customer service. Compaq redesigned its PCs, making modular assembly of certain features possible. The company adopted a new assembly policy so that, rather than assembling all PCs at the plant locations and distributing them through a network of warehouses, it will now assemble components to form a “standard” base that is specialized to customer demand through modular assembly performed by distributors. The goal of improving customer service has led to a new assembly policy which, in turn, has led to a modified product design and logistics network.

The MacDonald’s Restaurant chain provides yet another example. The fast-food business is driven by the need to provide fresh food to customers upon demand. MacDonald’s purchases beef in countries noted for their beef-raising capabilities, maintains a network of warehousing centers and operates a multitude

of restaurants around the world that quickly satisfy customer demands on an assembly-to-order basis.

In some industries (e.g., especially high-technology industries such as computers), rapidly evolving innovations in technology have shortened product life cycles, placing a premium on quick response and timely delivery to customers. However, other industries (e.g., process industries) have not experienced such high rates of product innovation and typically place a premium on capacity utilization. This paper tends to focus on the high-technology industries, so it should be emphasized that a company's logistic network must be designed in relationship to the marketplace in which it competes. Thus, it may be necessary to adapt the perspective presented in this paper to accommodate the needs of specific industries.

The body of this paper is composed of four sections. Sections 2.0, 3.0 and 4.0 address strategic, tactical and operational decisions, respectively. Each section reviews related literature and discusses relevant modeling issues. Collectively, a vast body of literature is related to these three levels, so we focus on the most relevant work in these reviews. Some papers do not address purely strategic or purely tactical issues as we define them in this paper, so we have taken some liberty in assigning papers to sections 2.0 and 3.0. Interest in global logistics networks has grown rapidly in parallel with the global economy. Recent reviews [Thomas and Griffin (1995); Vidal and Goetschalchx (1997); Ganeshan, Jack, Magazine and Stevens (1999); and Cohen, and Huchzermeir (1999)], books [Wood, Barone, Murphy and Wardlow (1995); Bramel and Simchi-Levi. (1997); and Ernst, Kouvelis, and Dornier (1998); Lee (1998); and Tayur, Ganeshan, and Magazine (1999)], and special issues of *Management Science* [Graves and Fisher (1997)] and *IIE Transactions* [Lee 1997]) describe the state-of-the-art. Section 5.0 gives a brief summary of conclusions and suggestions for further research.

## **2.0 THE STRATEGIC LEVEL**

This section addresses the strategic level, which designs the logistics network by prescribing facility locations, production technologies, and plant capacities. The network must integrate with suppliers and transportation channels to customers. In addition to labor and transportation costs, it must consider other issues such as the infrastructure, general business environment, closeness to markets and to suppliers, taxes

and duties, strategic alliances and joint ventures. In general, the production and assembly of each product may be accomplished in a set of related facilities, each of which might be located in a different country.

In the first sub-section, we review literature that is relevant to strategic-level decisions. In the second sub-section, we present a prototype formulation to focus our discussion of relevant modeling issues.

**2.1 Literature review.** A considerable amount of research has been directed towards strategic aspects of domestic production/distribution networks [e.g., Cohen and Lee (1985), Cohen, Lee, and Moon (1988); Cohen and Lee (1988); Graves, Kletter, and Hetzel (1998)]. Historically, research has addressed specific aspects of the logistics system, for example, distribution [e.g., Geoffrion (1977) and Geoffrion and Powers (1995)], facility location [e.g., Van Roy and Erlenkotter (1982), Van Roy (1983) (1986), Verter and Dincer (1995a), and Revelle and Laporte (1996), Francis et al. (1992), Tompkins et al. (1996)] and capacity expansion [e.g., Luss (1982) and Rajagopalan, Singh, and Morton (1998)]. We focus on the literature that deals with international networks from a systems perspective.

Verter and Dincer (1992) reviewed the literature related to global manufacturing, concluding that it is vital to integrate decisions that determine location, capacity acquisition and technology selection, and we discuss this issue further in a later section. Verter and Dincer (1995a) pointed out that few studies have dealt with the international aspects of strategic production-distribution models, and Verter and Dincer (1995b) overviewed the literature that deals with strategic issues relevant to global logistics networks. They concluded that there exists a limited set of models that addresses these issues and recommended that future research develop more efficient methods to prescribe optimal configurations.

Cohen and Lee (1989) built upon their work on domestic production/distribution systems, describing a model for designing an international network and managing material flows within the network. Their model maximizes after-tax profit subject to constraints on facility capacity, demand requirements, material balance and government requirements. They proposed a global manufacturing strategy, which combines strategies for plant operation (regional, consolidation, product focus, process focus and vertical integration), supply (centralized control, regional control, consolidation and diversification) and distribution (consolidation, co-location and market service). They did not present a mathematical model, but they

apparently did not prescribe plant locations or production technologies. They did, however, describe a numerical example, demonstrating application of their model to analyze tradeoffs involved in producing personal computers in an international network.

Kouvelis and Rosenblatt (1997) formulated a mixed integer programming model to prescribe an optimal design for an international logistics network. Their model focused on policies that individual countries adopt to attract international trade, including taxation, subsidized financing and local content rules. They presented numerical examples that demonstrate the sensitivity of the global network design to even small changes in the policies of just one country.

Taylor (1997) proposed a mixed integer program that prescribes technologies, capacities and tooling to minimize cost for global manufacturing and assembly. He presented several numerical examples that demonstrate model application in production sourcing and capital procurement. Taylor's model focuses on production technologies but, apparently, does not deal with designing the production/distribution network.

The issues involved in prescribing plant and warehouse locations in a global logistics network may differ from those traditionally used to locate plants. MacCormack et al. (1994) favored locating in developing markets or regionalized trade blocks, especially in countries with adequate infrastructure. They proposed a four-phased analysis: identifying the core competency of the firm; studying the regional manufacturing configuration, market access, risk management, customer demand, and impact of production technologies; generating a set of potential sites based on the infrastructure; and ranking potential sites using quantitative methods. Core competencies form the unique competitive basis of the company and may involve customer service, product quality and technological leadership, product and/or process attributes, and/or process flexibility. Rather than using only a traditional cost analysis, Bartmess and Cerny (1993) recommend that location be based on core competencies of the firm. To identify the best network configuration, they formulated a return-on-investment model, which considers exchange rates, political uncertainties, taxes, transfer prices, company costs, and levels of risk, but they described no quantitative means of evaluating alternative designs.

Global logistics networks involve a number of issues that are not encountered in domestic systems.

According to Fagan (1991), global sourcing may improve supplier availability and product quality, but it may entail the disadvantages of greater risks, higher communication and distribution costs, and larger inventory buffers that result in longer and more uncertain lead times. Monezka and Trent (1991) described a four-step procedure for successful global sourcing, and Davis (1992) discussed inconveniences and possible negative consequences. Ohmae (1989) stressed the importance of strategic alliances in global systems. In addition to establishing a competitive posture based upon core competencies, Hise (1995) has noted that timing is of crucial importance in global competition. Evolving trade agreements (e.g., North American Free Trade Agreement (NAFTA), European Union (EU), Association of South Eastern Nations (ASEAN)) eliminate trade barriers between countries and tend to homogenize taxes and other rules among countries, so they will influence the design and operation of future global logistics networks.

Few studies have addressed the uncertainties associated with strategic aspects of global logistics networks. Kogut (1985) recommended that flexibility, which arises from providing excess capacity in the form of flexible technologies and using a variety of sources, be used as a response to fluctuations in exchange rates, government policies, and competition. Lessard and Lightstone (1986) and Carter and Vickery (1989) discussed risks associated with global logistics and potential means of hedging against them. Hodder and Dincer (1986) formulated a quadratic program that combines plant location, product flow, and financial variables. They modeled selling price and fixed costs as random variables but solved their model using an approximation method. They concluded that modeling exchange rates as random variables leads to programs that are extremely difficult to optimize. Cohen and Kleidorfer (1993) incorporated location, capacity, product mix, and material and cash flow in a multi-period stochastic program. They proposed several interacting stochastic sub-models but gave no formulation or solution details.

**Modeling issues.** In this section, we present a prototype formulation to focus discussion on modeling issues. We note that further research is needed to refine our prototype formulation to yield a computationally effective model that deals with all relevant issues.

We assume that the structure of each product can be represented by an assembly tree in which each node represents a task (operation) and each arc represents the transit of components between tasks (operations).  $A_i$

denotes the set of tasks that must immediately precede task  $t$ . For example, if task  $t$  were an assembly operation,  $A_t$  would represent the set of tasks related to components assembled by task  $t$ .  $B_t$  denotes the set of tasks that must immediately succeed task  $t$ . In an assembly tree,  $|B_t| = 1$  for all nodes except for the root node, which represents the finished product and has  $|B_t| = 0$ .

We use three types of decision variables to prescribe the strategic logistics network. Selecting from a set of  $K$  possible locations, binary decision variable  $Z_k = 1$  if location  $k$  ( $k \in K$ ) is “opened” and 0 otherwise. To prescribe the technology for each operation, binary decision variable  $Y_{kmrt} = 1$  if resource  $r$  is employed at location  $k$  to complete task  $t$  on product  $m$  and 0 otherwise. Finally, decision variable  $X_{kk'mrt}$  prescribes the number of products of type  $m$  for which task  $t$  is performed using resource  $r$  at location  $k$  and then transported to location  $k'$  for the following operation. To represent the sale of finished products to customers, we specialize the indices of variable  $X_{kk'mrt}$  to  $X_{wcmr}^0$  in order to denote the number of finished products of type  $m$  transported (i.e., task  $t$  specializes to “transport”  $t^0$ ) from warehouse  $w$  (i.e., location  $k$  specializes to the location of warehouse  $w$ ) to customer  $c$  (i.e., location  $k'$  specializes to customer location  $c$ ) using transportation mode  $r$  (i.e., resource  $r$  specializes to transport mode  $r$ ).

Before presenting the prototype formulation, we summarize notation for reader convenience.

## Notation

### Indices

$c$	customers	$c \in C$
$k$	locations	$k \in K$
$m$	product types	$m \in M$
$r$	resource types	$r \in R$
$t$	tasks required to produce product $m$	$t \in \Psi_m$
$w$	warehouses	$w \in W$

### Parameters

$a_{kmrt}$	amount of resource $r$ required to perform task $t$ on product $p$ at location $k$
$\mathcal{C}_k^I$	investment cost to open location $k$
$\mathcal{C}_{kk'mt}^B$	border crossing cost from location $k$ to $k'$ for 1 unit of product $m$ after task $t$ is performed
$\mathcal{C}_{kmrt}^P$	cost to process task $t$ on product $m$ using resource $r$ at location $k$
$\mathcal{C}_{kmrt}^R$	fixed cost to provide resource $r$ at location $k$ to complete task $t$ on product $m$
$\mathcal{C}_{kk'mt}^T$	cost to transport one unit of product $m$ from location $k$ to $k'$ after task $t$ is performed
$D_{cm}$	number of products of type $m$ demanded by customer $c$

$Q_m$  upper bound for production of product  $m = \sum_c D_{cm}$

$U_{kmrt}$  availability of resource  $r$  at location  $k$  to perform task  $t$  on product  $m$

$\Pi_{wcm}$  the price that customer  $c$  must pay to purchase one unit of product  $m$  supplied by warehouse  $w$

### Sets

$A_t$  immediate predecessors of task  $t$

$B_t$  immediate successors of tasks  $t$  ( $|B_t| = 1$  for an assembly tree structure)

$C$  customers

$K$  locations

$K_t$  locations at which task  $t$  could be performed if opened  $K_t \subseteq K$

$M$  product types

$R$  resource types

$R_t$  resource types that can complete task  $t$

$W$  warehouses

$\Psi_m$  tasks required to produce product  $m$

### Decision Variables

$X_{kk'mrt}$  number of products of type  $m$  for which task  $t$  is performed using resource  $r$  at location  $k$  and then transported to location  $k'$  ( $t' \in B_t$ )

$Y_{kmrt}$  1 if resource  $r$  is employed at location  $k$  to complete task  $t$  on product  $m$ , 0 otherwise

$Z_k$  1 if location  $k_i$  is “opened”, 0 otherwise

note:

$$X_{wcmrt^0} \Rightarrow X_{kk'mrt}$$

number of finished products of type  $m$  transported ( $t^0 \Rightarrow$  “transported”)

from warehouse  $w$  ( $w \Rightarrow$  location  $k$ ) to customer  $c$  ( $c \Rightarrow$  location  $k'$ ) using mode  $r$  (i.e., resource  $r$ )

We now present our prototype formulation of strategic-level decisions.

Objective: Maximize Profit

$$\begin{aligned} \text{Max } Z = & \sum_{wcmr} \Pi_{wcm} X_{wcmrt^0} \\ & - \sum_k \mathcal{E}_k^I Z_k - \sum_{kmrt} \mathcal{E}_{kmrt}^R Y_{kmrt} - \sum_{kk'mrt} (\mathcal{E}_{kk'mt}^B + \mathcal{E}_{kmrt}^P + \mathcal{E}_{kk'mt}^T) X_{kk'mrt} \end{aligned} \quad (1)$$

Subject to:

$$\sum_{wr} X_{wcmrt^0} = D_{cm} \quad c \in C, m \in M, t^0 \Rightarrow \text{transport} \quad (2)$$

$$\sum_{k'' \in K_{t'}} \sum_{r \in R_{t'}} X_{k''kmrt''} - \sum_{t' \in B_t} \sum_{k' \in K_{t'}} \sum_{r \in R_{t'}} X_{kk'mrt} = 0 \quad m \in M, t \in \Psi_m, k \in K_t, t'' \in A_t \quad (3)$$

$$X_{kk'mrt} \leq Q_m Z_k \quad m \in M, t \in \Psi_m, k \in K_t, t' \in B_t, k' \in K_{t'}, r \in R_t \quad (4)$$

$$\sum_{k' \in K_{B_t}} a_{kmrt} X_{kk'mrt} \leq U_{kmrt} Y_{kmrt} \quad m \in M, t \in \Psi_m, k \in K_t, r \in R_t \quad (5)$$

$$\sum_{k \in K_t} Z_k \geq 1 \quad m \in M, t \in \Psi_m \quad (6)$$

$$Y_{kmrt} \leq Z_k \quad m \in M, t \in \Psi_m, k \in K_t, r \in R_t \quad (7)$$

$$Y_{kmrt} \in \{0, 1\} \quad m \in M, t \in \Psi_m, k \in K_t, r \in R_t \quad (8)$$

$$Z_k \in \{0, 1\} \quad k \in K \quad (9)$$

$$X_{kk'mrt} \geq 0, \text{ Integer} \quad m \in M, t \in \Psi_m \cup \{t^0\}, k \in K_t, k' \in K_t, r \in R_t \quad (10)$$

The objective (1) is to maximize profit. A revenue of  $\Pi_{wcm}$  accrues for each of the  $X_{wcmr}^0$  sales. To calculate profit, we subtract the fixed cost to open location  $k$  (denoted by  $\mathcal{C}_k^I Z_k$ ); the fixed cost of providing resource  $r$  at location  $k$  to complete task  $t$  on product  $m$  (denoted by  $\mathcal{C}_{kmrt}^R Y_{kmrt}$ ); and the variable costs associated with border crossing, manufacturing operations and transportation (denoted by  $(\mathcal{C}_{kk'mt}^B + \mathcal{C}_{kmrt}^P + \mathcal{C}_{kk'mt}^T) X_{kk'mrt}$ ).

Inequality (2) assures that the demand of each customer for product  $m$ ,  $D_{cm}$ , is satisfied. Equality (3) invokes a flow balance, assuring that the flow of product  $m$  into task  $t$  (at location  $k$ ) from *each* immediately preceding task  $t'' \in A_t$  (at location  $k''$ ) equals the flow of product  $m$  from task  $t$  to immediately succeeding task  $t' \in B_t$  (at location  $k'$ ). Inequality (4) relates  $X$  and  $Z$  decision variables, assuring that task  $t$  on product  $m$  cannot be performed at location  $k$  if that location is not opened. Inequality (5) relates  $X$  and  $Y$  decision variables, invoking the capacity of the resource  $r$ , which is prescribed to perform task  $t$  on product  $m$  at location  $k$ . The capacity of resource  $r$  provided at location  $k$  for task  $t$  on product  $m$  may also be prescribed, for example, by defining  $r$  to denote resource type as well as its capacity (availability). Setting a particular  $Y_{kmrt} = 1$  would then select resource  $r$  and its availability  $U_{kmrt}$ . Of course, this convention would require additional constraints of the form  $\sum \sum Y_{kmrt} = 1$  in which  $r$  is summed over the set of resource types that can complete task  $t$ ,  $R_t$ , as well as the set of capacities for each resource type. The model would then prescribe one resource to perform task  $t$  on product  $m$  at location  $k$  as well as the capacity of that resource. Inequality (6) requires that at least one facility, which can perform task  $t$  for product  $m$ , be opened. Inequality (7) relates  $Y$  and  $Z$  decision variables, assuring that location  $k$  employs technology (i.e., resource)  $r$  only if it is opened.

Finally, constraints (8) – (10) impose binary and integer requirements.

Formulation (1)-(10) exhibits an interesting structure. Equalities (2) and (3) invoke task precedence relationships and impose restrictions related to network flow constraints. Equality (3) requires that the flow of product  $m$  from task  $t$  to its immediate successor,  $t'$ , equal the flow from immediate predecessor  $t''$  to  $t$ . However, the assembly tree structure requires a constraint of type (3) for each  $t'' \in A_t$ , so (3) does not represent a classical network flow problem. It does, however, represent bill-of-material (BOM) relationships associated with assembly operations. With  $Z_k$  variables fixed to binary values, inequality (4) becomes an upper bound for flow on an arc in this network. Constraints can be decomposed to form an independent flow problem involving constraints (2), (3) and (4) for each product. Fixing  $Y_{kmrt}$  variables to binary values introduces resource-capacity limitations on the performance of task  $t$  on product  $m$  at location  $k$ . Alternative production configurations could be represented by appropriate constraints. For example, if resource type  $r$  could be used to perform all tasks assigned to location  $k$ , then (5) could be formulated as

$$\sum_{m \in M} \sum_t \sum_{k' \in K_{B_r}} a_{kmrt} X_{kk'mrt} \leq U_{kr} Y_{kr} \quad k \in K, r \in R \quad (5')$$

in which the summation on  $t$  includes the subset of tasks in set  $\Psi_m$  that can be performed at location  $k$  by resource type  $r$ .

Since international logistics networks frequently involve production as well as assembly, the structure of the strategic-level model does not conform to traditional production models. Constraints (1)-(3) evidence this complication in that they do not form pure network flow constraints.

Because the strategic level may involve a relatively lengthy planning horizon, decision makers would typically not have enough information to specify all parameters with certainty. Strategic-level decisions entail a relatively high level of uncertainty associated, for example, with demand, political environment, and exchange rates. In fact, it may be difficult even to specify the set of products,  $M$ , in great detail over a long planning horizon since most products tend to have short life cycles in today's marketplace. Thus, it may be necessary to treat parameters like  $D_{cm}$ ,  $a_{kmrt}$ ,  $U_{kmrt}$ ,  $\Pi_{wcm}$ ,  $\mathcal{E}_{kk'mt}^B$ ,  $\mathcal{E}_{kmrt}^P$ , and  $\mathcal{E}_{kk'mt}^T$  as random variables. These considerations lead to a stochastic, integer formulation.

Another issue involves time dependency. The prototype formulation (1)-(10) is a static model in that the decisions, which are prescribed at the time the model is implemented, fix the design of the logistics network for the entire planning horizon. In practice, it may be possible to add facility locations and plant capacity incrementally over time. In such a case, the parameters and decision variables in formulation (1)-(10) would have to be amended by adding a subscript to designate time period, for example, years 1, 2, ..., 5. This consideration would lead to a stochastic, time-dependent, integer program, a type of model that presents exceptional computational challenges.

Depending upon the application, other issues may also be relevant. For example, the transportation system employed may have a cost structure that is most appropriately modeled as a concave function of the quantity transported. Furthermore, it may be of interest for the model to prescribe whether flexible or dedicated technologies should be employed [e.g., Cetinkaya and Falkner (1995) and Benjaafar and Gupta (1998)]. In addition, it may be important to model transfer pricing explicitly, so that the network design reflects this important determinant of taxes. Typically, transfer pricing introduces nonlinearities and results in a nonconvex model [Vidal and Goetschalckx (1998)]. Transfer pricing may be an issue in strategic, tactical and operational levels.

Finally, we note that this prototype formulation is related to Geoffrion's (1974) model for designing multi-commodity distribution systems. He successfully solved his model through a specialized application of Benders decomposition. Geoffrion's model deals with a set of plants that produce finished products, which are then stored in distribution centers for shipment to various customer zones. His model focused on distribution, prescribing locations for distribution centers and the capacity of each. The prototype formulation (1)-(10) extends Geoffrion's focus to allow parts and subassemblies to be processed in a series of plants, forming a larger, multi-echelon logistics network. Geoffrion's model does not reflect suppliers, assembly BOMs, stochastic aspects, time dependencies or other considerations important to international logistics networks. We now turn attention to the tactical level.

### **3.0 THE TACTICAL LEVEL**

The tactical level prescribes material flow management policy, including production levels at all plants, assembly policy, inventory levels, and lot sizes. It deals with material flow from suppliers to production facilities, to assembly plants, through warehouses and on to customers. The strategic level must deal with a number of uncertainties, and the tactical level, which deals with the time horizon of, perhaps, 6-24 months, affords an opportunity to refine production plans to compensate for political and financial processes as they unfold. Products ordered for delivery in the near term may be known with certainty but, still, later periods in the tactical horizon may be subject to some degree of uncertainty.

Customers demand highly individualized products within short lead times, so product variety is a primary issue at the tactical level. Customer service is a function of the assembly policy, which can, for instance, require finished-product inventories or assemble-to-order operation. If *immediate* delivery of finished products is critical, customized products must be assembled and held in inventory [e.g., Schmidt and Nahmias (1985) and Rosling (1989)]. In addition, production lot size must be determined at the tactical level [e.g., Afentakis, Gavish, and Karmarkar (1984); Afentakis and Gavish (1986); Atkins Queyranne, and Sun (1992); Axsater and Nuttle (1987)]. In assemble-to-order systems [e.g., Glasserman and Wang (1996), Schraner (1996), and Zhang (1996)], in which only components - not products - are inventoried, the challenge is to respond to consumers within pre-specified times with no finished-product inventory. To achieve this, product designs can be based on interchangeable modules that are assembled into different final products on demand, customizing them as required. To be profitable, a company must achieve a favorable trade-off between service level (i.e., leadtime) and inventory cost (i.e., fill rates).

The tactical level considers both production and transportation. Such decisions are often made separately, but that is possible only when the decisions have few interdependencies. The question is how to assign production to plants in order to minimize production, changeover, holding, and transportation costs. In the multi-plant environment, each assembly operation must be assigned to one plant from among the candidates that offer the required technological capability and production capacity. Even though the strategic level develops a long-range plan for assignment of operations to locations, this decision must be refined at the tactical level as demands, exchange rates, political environment, and other factors become better defined.

The first sub-section in this section reviews literature relevant to tactical-level decisions. The second sub-section discusses relevant modeling issues.

**3.1 Literature review.** Cohen, Fisher and Jaikumar (1989) presented a preliminary model for coordinating procurement, manufacturing, and distribution in global networks. They discussed many of the factors that are germane to international networks, including economies of scale, duties and tariffs, currency exchange rates, global sourcing, and country-specific considerations such as local sourcing rules and tax rates. Their model incorporates many of these factors, maximizing after-tax profits subject to constraints on material supply, material requirements, plant shipments, market demand, market cash flows, plant capacities and local content rules. They also discussed techniques for dealing with random currency fluctuations. Marketing and financial considerations are the focus of this model, which is a mixed integer program with nonlinearities introduced by variables that determine transfer prices and allocate overhead to plants. Their model is based on a three-level network, composed of vendors, plants and markets, and does not deal with assembly, plant-to-plant transfers or warehousing.

Lee and Billington (1992) discuss potential problems and opportunities associated with managing supply chain inventory. Arntzen, Brown, Harrison and Trafton (1995) described practical issues encountered by Digital Equipment Corporation in its international logistics network and discussed application of a large-scale, mixed integer linear program to minimize the sum of fixed and variables costs. The latter included the costs of production, inventory, shipping, and duties.

Vidal and Goetschalckx (1996) modeled the impact of exchange rates and supplier reliability on system configuration in a mixed integer program (MIP) and demonstrated the sensitivity of the global logistics network design to these parameters. They classified relevant factors as those that can be modeled with a high degree of accuracy, those that can be modeled adequately by invoking assumptions, and those that are very difficult to model. They emphasized the need to address uncertainties and noted that there is currently no generally accepted quantitative methodology for dealing with global logistics networks. Vidal and Goetschalckx (1998) described a detailed model to maximize after-tax profits, considering transfer prices and transportation costs. They presented a heuristic to solve their model, which is not convex.

Canel and Kumawala. (1997) proposed a MIP model to optimize the global supply chain for a single product, however it does not prescribe transfer prices and transportation costs. Dasu and de la Torre (1997) modeled a multi-national company with partially owned subsidiaries that must compete with each other as free trade develops, determining production quantities for each plant and sales prices that are responsive to exchange-rate fluctuations. They presented a solution methodology and a numerical example, demonstrating application to the fiber industry in Latin America.

Few studies have addressed the uncertainties associated with tactical aspects of global logistics networks. Cohen and Lee (1988) formulated stochastic sub-models for a serial production process but concluded that optimizing all sub-models is not tractable, so they proposed a heuristic solution method. Cohen and Lee (1988) claimed that many uncertainties and qualitative factors may be analyzed through the specification of different scenarios and sensitivity analysis. They noted that there is currently no formal and consistent way to represent BOM constraints (i.e., assembly operations as in constraints (2)-(4)). Cohen, Fisher, and Jaikumar (1989) fixed transfer prices and allocated overhead to reduce their model to a tractable MIP. Kogut and Kulatilaka (1994) proposed a model to prescribe the shifting of production between plants in two countries. They developed a stochastic dynamic program to deal with randomly fluctuating exchange rates. Cole (1995) proposed a more limited MIP model of production and distribution that considered stochastic safety stock under normally distributed demand.

**3.2 Modeling issues.** Considering formulation (1)-(10) as a prototype for a tactical-level model, we see that the strategic level fixes  $Z_k$  and  $Y_{kmt}$  decision variables relative to the description of products, demands and exchange rates available when the model is implemented. Decision variables  $X_{kk'mrt}$  represent the material flow management decisions emphasized at the tactical level. More information is available to the tactical level as random processes unfold, so the relative levels of uncertainty are less than in the strategic level. The tactical level makes flexible use of the plant capacities made available by strategic-level decisions.

Basic issues that must be modeled at the tactical level include:

(1) what is the optimal assignment of operations to plants, taking into account plant capacities that result from strategic decisions and actual product demand that develops,

- (2) what is the optimal assembly policy for each product,
- (3) what is the optimal inventory level for each subassembly, taking into account the coordination of shared inventories and interdependent demand, and
- (4) what is the optimal lot size for assemble-to-order components.

Relative to formulation (1)-(10), parameters and decision variables must be amended by adding a subscript to designate time period, for example, months 1, 2, ..., 18. This consideration again leads to a challenging, stochastic, time-dependent, integer program.

Many of the basic issues seem to have been well structured by prior work and research needs are widely recognized. In a critical review of global supply chain models, Vidal and Goetschalckx (1997) emphasized the need for more comprehensive models as well as specialized solution methods. They noted that there “exists a lack of research on MIP models for the strategic design of global supply chain systems” and that “most models do not include single sourcing, inventory costs, and BOM constraints,” which are fundamental to assembly systems. They also pointed out that “Most research addresses a single component of the overall production-distribution system, such as purchasing, production and scheduling, inventory, warehousing or transportation. To date there exists little research that addresses the integration of such single components into the overall supply chain. “... there exist many opportunities for developing more comprehensive global supply chain models that include BOM constraints, more stochastic factors and qualitative factors that are important in the global environment.” They also observed that solutions methods have been limited to Benders decomposition [Geoffrion (1974)] and factorization methods [Brown and Olson (1994)], and identified a primary research need as the development of specialized methods of solution.

#### **4.0 THE OPERATIONAL LEVEL**

The operational level schedules operations to assure in-time delivery of final products to customers. In contrast to the strategic and tactical levels, little research has been directed towards scheduling multi-echelon, multi-national operations. One reason for this may be that scheduling problems may be viewed as specific to the degree of management’s centralization (or decentralization), the performance measures used to evaluate managers, and the process configuration (e.g., single machine, parallel machines, flow shop, job shop,

cellular organization). Nevertheless, the operational level can significantly affect customer service, so it is an important component in providing a unified logistics system.

Our discussion focuses on coordinating schedules for multi-echelon assembly systems in which each process may be located in a different country, and we describe application of optimization to coordinate material flow in such a system. Our approach to coordination is represented by constraints; for example, the strategic level determines system capacity and the tactical level prescribes material flow, setting the stage for scheduling by positioning inventories. We propose use of optimization as a means of fulfilling a particular customer-service objective to the extent possible, given the constraints imposed by strategic and tactical levels. To focus on multi-echelon coordination, we assume implicitly that each process is performed by a unique workstation dedicated to a specified set of products. Our presentation may be adapted to address specific industries that might have different needs.

Companies having dispersed locations in several countries may gain many advantages by reducing the time and cost associated with production and delivery. On the other hand, coordinating the underlying logistics network becomes more difficult. Demand for products occurs at points in time when customers place orders. The focus at the operational level is on where and when to assemble components to minimize the time interval from order arrival to order delivery at the customer's site. We intend for our terminology to be generic so that an "operation" can represent the processing of a part, a component, a subassembly, a module, or the end product in batches of size one or larger.

It is more difficult to answer these questions for multi-component products that are assembled in networks than it is for single-component products that require no part coordination. In environments that involve multiple components, both serial and parallel operations must be considered. More generally, connections between processing facilities in networks must be allowed arbitrary structure.

The first sub-section in this section reviews literature relevant to operational-level decisions. The second sub-section discusses modeling issues.

**4.1 Literature review.** We know of no research that has focused specifically on scheduling in multi-national logistics networks. However, the literature describes prior research on two topics related to the operational level: scheduling assembly operations and scheduling in networks. We will give a short review of each topic.

Little (1994) reviews case studies for scheduling assembly systems. Russell and Taylor (1985) studied scheduling in an assembly shop, evaluating dispatching policies based on priority rules. Each job consists of several manufacturing and assembly operations, which define a tree precedence structure. The shop configuration consisted of a number of machine centers, which were dedicated to manufacturing operations, and one machine center, which was assigned only assembly operations. Russell and Taylor treated labor as a scarce resource that had to be shared between the machine centers. They considered no transportation times nor alternative machine centers for operations. They analyzed several objectives related to job completion time (e.g., mean flow time, mean tardiness and percent jobs tardy) and studied the impact of priority rules in meeting these different objectives.

Phillips, Stein and Wein (1997) studied scheduling in networks. They assumed that each job consists of a single operation, which can be performed by any machine in a set of identical (unrelated) machines. The machines are connected by a network defining distances between machines by shortest paths between pairs of nodes in the network. Each job has a certain starting node from which it proceeds. They investigated two objectives: makespan and sum of completion times. To solve the problem, they devised approximation algorithms.

Flipo and Finke (1997) investigated a similar problem in network scheduling. They also assumed that a job consists of a single operation and dealt with networks in which nodes relate to production facilities, warehouses and customers, and arcs represent transportation links. The problem combined production and distribution in a setting in which each facility had several production lines dedicated to certain product types with different production rates. Moreover, they considered changeover times if products of different types were produced in sequence on the same line. They modeled the system as a network flow problem with the objective of minimizing the sum of production, changeover, holding, and transportation costs.

Huang and Xu (1998) investigated a multi-stage, multi-item network scheduling problem. They

considered storage space limitations and the production capacities of workstations. Their model minimized the total cost of holding, processing, transporting, and schedule delay by prescribing the times at which jobs enter the system and the time-dependent processing route for each job. They adapted a network algorithm to solve the problem, invoking the simplifying assumption that operations need not be coordinated.

**4.2 Modeling issues.** Tactical-level decisions position inventories for use by the operational level. The parts and subassemblies needed for each assembly operation must be available before the operation can begin. This interface between the tactical and operational levels of assembly systems has been studied by Chen and Wilhelm (1993) (1994) (1997).

A model of the operational level must be based on structural assumptions concerning the products and the logistics network. For example, one may assume, without loss of generality, that each location has only one workstation. If a location actually has more than one workstation, each may be treated as a separate location. We denote the graphical representations of the logistics network and the products by  $G_1$  and  $G_2$ , respectively. Nodes of  $G_1$  represent locations (workstations); and edges, transportation links between them. Edge weights give information about the distances between the respective locations. The questions of when and where to move the products in the network are critical for achieving efficient resource utilization.

Every product has an associated graph  $G_2$ , which describes its BOM and feasible sequences of assembly.  $G_2$  has a special structure, which is an in-tree. An in-tree consists of three kinds of nodes: nodes without predecessors (leaves), nodes without successors (root), and nodes with predecessors and successors (intermediates). Intermediate nodes have an arbitrary number of predecessors but only a single successor; a leaf has no predecessor and a single successor node, and a root has an arbitrary number of predecessor nodes but no successor node.

Each node in an in-tree can be assigned to a layer. Nodes belonging to the same layer have the same number of components in the backpath to the root node. An in-tree has as many layers as there are components on the longest path from a leaf node to the root. The layers describe the sequence in which components must be made available to assemble the product. We use the term “component tree” to indicate an in-tree with a given layer structure.

Each product  $j$  is made from a set of components  $S_j = \{S_{ij} \mid i = 1, \dots, n(l), l = 1, \dots, n(j)\}$  that must be joined by assembly operations.  $n(l)$  denotes the number of components in layer  $l$  and  $n(j)$  is the number of layers that compose product  $j$ . Component  $S_{ij}$  is assembled on layer  $l$  by joining its predecessor components  $S_{i,l-1,j}$  from layer  $l-1$ . We denote the corresponding assembly operation by  $T_{ij}$ . Component  $S_{1,n(j),j}$  represents the finished product  $j$  as well as the root of the component tree.

Figure 1 gives an example of graphs  $G_1$  and  $G_2$ . The logistics network depicted consists of nine locations ( $k$ ) that are connected by ten transportation links ( $(k, k')$ ); edge weights are not shown. Product  $j$  consists of five components  $S_{ij}$  related in three layers of the component tree and can be assembled if the constraints represented by the arcs are observed. Node  $S_{13j}$  represents the final product.

Insert Figure 1 here

Locations in the multi-national network may be in different time zones so that they might not all be available simultaneously in certain time intervals. Consider, for example, locations in Germany and California that operate for two eight-hour shifts, starting at 6am local time. Normalizing the time scale to Pacific time, the California location is active from 6am to 10pm and closed from 10pm to 6am. The German location is active from 9pm to 1pm and down between 1pm and 9pm Pacific time. If a location operates three shifts so that it is continuously active, downtime intervals are not defined.

Given a customer order, the operational-level problem is to determine where and when operations should be performed to meet given constraints and optimize the objective function. Two problem types exist:

(1)The order sequencing problem (OSP): locations (workstations) for assembly operations are fixed and there is a unique location (workstation) for each operation. This leads to an OSP in which one must determine the time when each operation is performed at each location in which the operation is performed.

(2)The network scheduling problem (NSP): each assembly operation can be performed at several candidate locations (workstations). This leads to a NSP in which one must decide where an operation is to be performed as well as when.

We use the term “job” to indicate a product that is ordered by some customer. Once an order is placed, it must be completed according to the product's component tree. A collection of jobs represents customer orders (i.e., demand) that must be fulfilled during the planning period. We assume that the following data are known at the operational level:

- (1) component trees for all jobs (i.e., products),
- (2) processing time  $p_{ij}$  for assembly task  $T_{ij}$
- (3) transport time  $q_{i,(i+1),jkk'}$  between locations  $k$  and  $k'$ ,
- (4) order arrival date  $r_j$  for job  $j$ ,
- (5) due date  $d_j$  for delivery of job  $j$ ,
- (6) intervals of location downtimes: the  $v$ -th interval associated with location  $k$  is given by  $[B_{vk}, F_{vk}]$ .

We use  $C_j$  to denote the completion time of job  $j$ , that is, the time at which job  $j$  is delivered to the customer. Different objectives related to completion times may be used at the operational level. It might be necessary to deliver the collection of jobs as quickly as possible. In this case, the scheduling objective is to Minimize  $C_{max} = \text{Minimum } \max_j \{C_j\}$ . On the other hand, if it is important to avoid late delivery, the scheduling objective should be to minimize a function of the total tardiness of all jobs, where tardiness for job  $j$  is defined as  $D_j = \max\{C_j - d_j, 0\}$ . Other scheduling objectives relate to the flow (throughput) time  $F_j = C_j - r_j$ . For example, it is often necessary to minimize the sum of the flow times.

Schedules must also observe different constraints. The most basic ones are:

- (C1) Each operation can be assigned to only one location at a time.
- (C2) Each location can only process one operation at a time.
- (C3) Jobs can only be processed in active intervals.

The OSP and NSP are to find a demand-satisfying schedule that minimizes a non-decreasing real function of job completion times. Standard mathematical programming formulations can be used to give a formal description of these problems [Blazewicz, Dror, and Weglarz (1991)].

**4.2.1 The order-sequencing problem (OSP).** In the OSP, the location (workstation)  $k$  at which each assembly operation must be performed is pre-determined. We use  $T_{ijk}$  to denote that the assembly operation

associated with component  $S_{ij}$  must be performed at location  $k$ . All data describing the logistics network can now be represented within the component tree. We use the term “assembly tree” to indicate a component tree that incorporates information about assembly locations. Figure 2 depicts an assembly tree for an order related to the component tree given in Figure 1b.

Insert Figure 2 here

The example shows that five operations must be completed over three layers at five different locations. Locations 1, 2 and 3 complete operations  $T_{11j1}$ ,  $T_{21j2}$ , and  $T_{22j3}$ , respectively; location 4 assembles components  $S_{11j}$  and  $S_{21j}$ . Location 5 completes the final assembly operation  $T_{13j5}$ , combining subassemblies  $S_{12j}$  and  $S_{22j}$ .

In order to represent the input data for the OSP, we assign weights to the nodes and arcs in the assembly tree. A node weight represents an operation processing time and an arc weight represents the transport time between two locations. Operation  $T_{ijk}$  requires processing time  $p_{ijk}$ . After operation  $T_{ijk}$  is completed at location  $k$  on layer  $l$ , the assembled component must be transported to location  $k'$  on layer  $l + 1$  for the next operation, requiring transport time  $q_{i,l(l+1)j,kk'}$ . Figure 3 extends the example shown in Figure 2, adding processing and transport times.

Insert Figure 3 here

The notation used to describe the OSP may be simplified because there is only one candidate location for each operation. Each operation is already defined uniquely by index  $ijl$ . Let  $A_j$  be the set of ordered pairs of operations  $(T_{ij}, T_{i,l+1,j})$  for each job  $j$ . Let  $E_k$  be the set of pairs of operations to be processed at the same location  $k$ . Due to technological and capacity constraints, pairs from  $A_j$  and  $E_k$  must not overlap. Operation  $T_{ij}$  requires processing time  $p_{ij}$ . The primary decision variable,  $x_{ij}$ , prescribes the starting time for each operation in an optimal schedule.

The objective of an OSP may minimize some function of job completion times. Constraints must ensure that operations observe precedence relationships, that each workstation performs one operation at a time and that a job can only be processed by the assigned location during an active interval. Finally, constraints must assure that each job is started but not before its release time  $r_j$ .

**4.2.2 The network-scheduling problem (NSP).** In the NSP, each assembly operation can be performed at a number of candidate locations (workstations). In this case, a job is not represented uniquely by an assembly tree. Component trees and the logistics network define the input data for the NSP. We introduce decision variable  $x_{ijk}$  to denote the start time of the  $i$ -th operation of job  $j$  on layer  $l$  at candidate location  $k$ .

The objective of an NSP may minimize some function of job completion times. Constraints must assure that operations observe precedence relationships, that each location processes no more than one operation at a time and that jobs are processed only during active intervals. Such a formulation is general enough to subsume most classical, multi-stage production scheduling problems, which invoke assumptions like the following ones. A job shop means that there may be a different sequence of operations for each job and a flow shop means that the sequence is the same for all jobs.

(a) One operation, one processor for each layer:

Sequential job shop:  $l = n(j), i = 1,$

Sequential flow shop:  $l = n(j), i = 1,$

Single machine:  $l = 1, i = 1.$

(b) One operation, multi processors for each layer:

Flexible job shop:  $l = n(j), i = 1,$

Flexible flow shop:  $l = n(j), i = 1,$

Parallel machines:  $l = 1, i = 1.$

(c) Multi operations, one processor for each layer:

General job shop:  $l = n(j), i = n(l),$

General flow shop:  $l = n(j), i = n(l),$

Single machine:  $l = 1, i > 1.$

(d) Multi operations, multi processors for each layer:

Gen-Flex job shop:  $l = n(j), i = n(l),$

Gen-Flex flow shop:  $l = n(j), i = n(l),$

Parallel machines:  $l = 1, i > 1.$

Both OSP and NSP models can address further details, including, for example, the following features:

- (a) If more than one component type is processed at a location, change-over time  $s_{j|k}$  could be added.
- (b) A location may hold some inventory of assembled components that could be used to satisfy a demand, with essentially zero processing time.
- (c) Components must be batched for transport between locations.

## 5.0 CONCLUSIONS

This paper reviews the literature that deals with strategic, tactical and operational decisions related to multi-national logistics networks. The strategic level designs the logistics network, including prescribing facility locations, production technologies and plant capacities. The tactical level prescribes material flow management policies, including production levels at all plants, assembly policy, inventory levels, and lot sizes. The operational level schedules operations to assure in-time delivery of final products to customers. These levels interact in several ways. First, higher levels establish constraints that affect performance at lower levels. For example, the strategic level determines process capacity, and the tactical level positions inventories for use by the operational level. Second, each level addresses a particular time frame, and these time frames must be integrated to assure seamless customer service. For instance, the operational level must assure that short-term material flow meets customer-service goals, coordinating strategic and tactical levels appropriately. Thus, an approach that unifies these three levels is necessary to design and operate a competitive, global logistics network.

This paper also discusses modeling issues that are relevant to each decision level. It is intended that these issues be generic, but different industries may place varying degrees of emphasis on specific issues. Thus, different industries may need to adapt the models described in this paper to allow them to compete most effectively in particular marketplaces. Finally, we observe that some aspects do not lend themselves to quantitative modeling and must be addressed by the experience and judgement of capable managers.

It is our hope that this work will foster insight into issues relevant to multi-national logistics problems and encourage development of algorithms that can solve actual, large-scale problems. Our ongoing

research is directed towards formulating specific models of the type described in this paper and towards developing effective solution methods.

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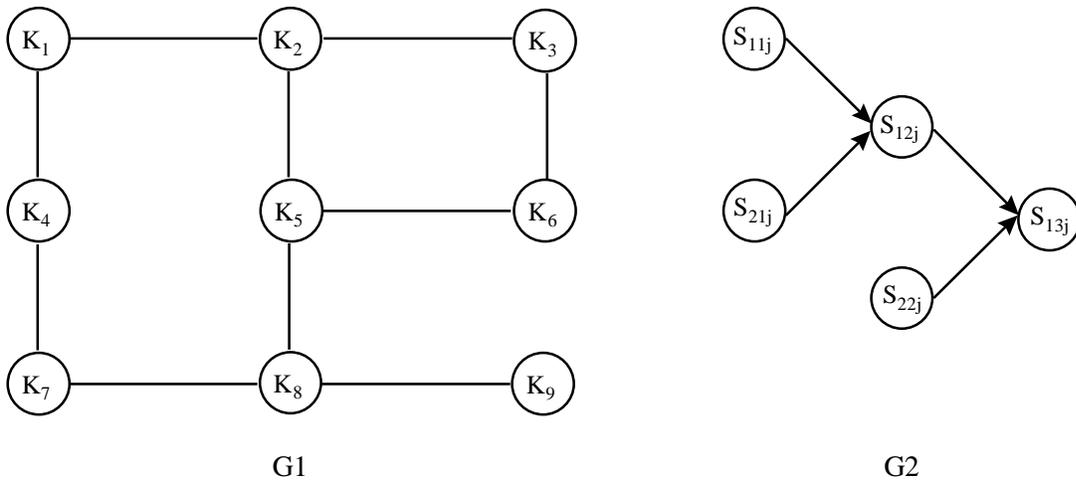


Fig.1: Graphical representation of (a) a logistics network,  $G_1$ , and (b) a component tree,  $G_2$

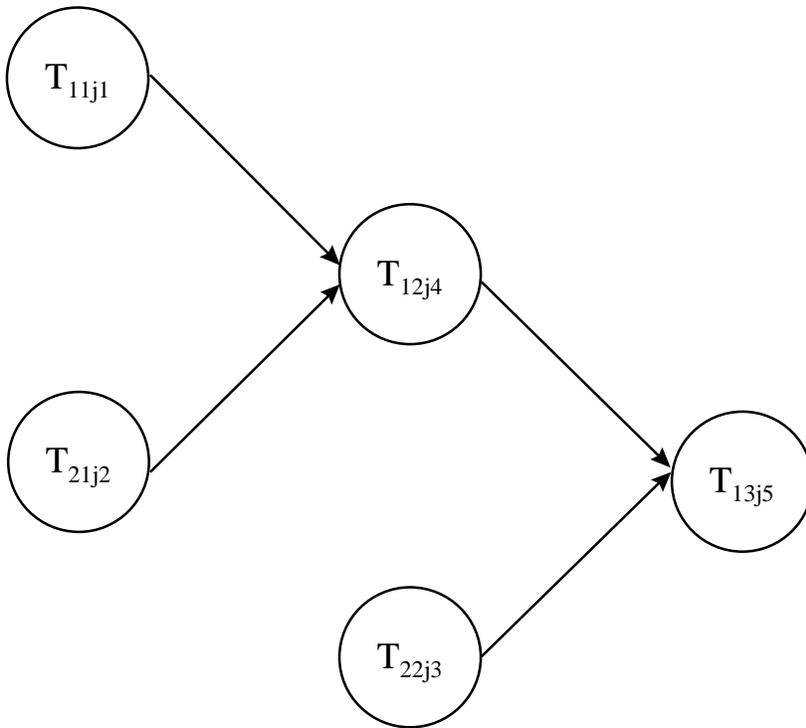


Fig.2: An example assembly tree

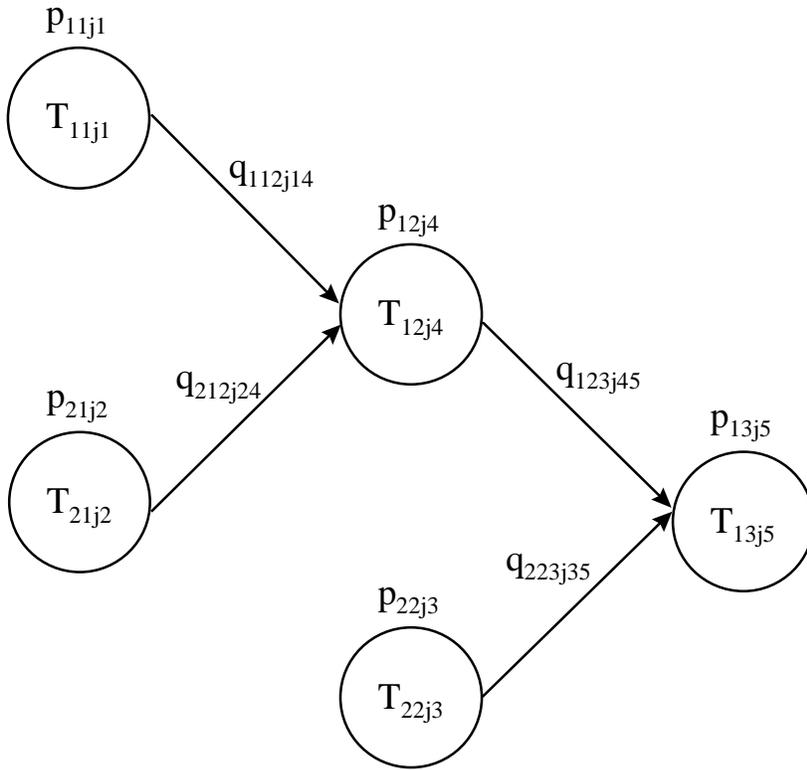


Fig.3: Example assembly t