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Title: Impacts of Lead Times Constraints on Global Supply Chain Decisions

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1 Introduction

In the current industrial and market context, the ability of a firm to offer short customer lead times is considered as a key to competitive success and survival. The customer lead time is commonly defined as the elapsed time between releasing an order and receiving it by the customer (Hsu and Lee, 2009). In the literature, different terminologies are used in reference to the customer lead time such as delivery lead time or simply lead time (LT). Many companies have recognized the significance of LT as a competitive weapon and have used time as a means of distinguishing themselves in the marketplace (Hsu and Lee, 2009). According to Eskigun et al. (2005), an important development in the automotive industry in recent years has been an increased interest in reducing the LT required to deliver vehicles from the assembly plants to the customer. Ouyang and Wu (1997) highlight that a shorter LT improves customer service level and increases the competitive advantage of business. Kaminsky and Kaya (2008) confirm this statement and state that firms need to quote short LTs to remain competitive in the market.

Unfortunately, the total LT required to manufacture and deliver a product is frequently larger than the LT imposed by the customer for that product, which reflects the customer LT constraint. If the customer demand is known enough time in advance, firms can meet customer LT constraints by anticipating purchasing, manufacturing and distribution activities. However, in real-world situations, the demand is often partially or totally uncertain, so firms generally keep inventories at different levels of the supply chain (SC) to shorten customer LT in order to be able to meet customer requirements. According to Feigin (1999), SCs often have many millions of dollars of capital tied up in inventories because of uncertainties in demand.

Nowadays, the globalization of market and the increasing competition force companies to reorganize their SC in order to reduce their costs and to remain competitive. Many real-world SCs have complex network structures, which consist of multiple layers of geographically dispersed manufacturing and distribution facilities and an international network of suppliers, in order to benefit from the low-cost locations, to access low-cost suppliers in developing countries, etc (Hammami et al., 2008, 2009). Components are therefore purchased worldwide and intermediate and final products are manufactured in many different facilities, generally located in different countries. Such a globalization of production activities and the reorganization of SC networks, which is expected to continue in the future, generally increase the LTs of purchasing, manufacturing, and transportation throughout the SC. Clearly, this impacts the customer LT and generally forces firms to keep higher inventories of upstream products and/or to reposition inventories closer to customers. In such a context, on one hand, the inventory costs may become very large. Indeed, in a complex SC where products and components of products are manufactured in many different facilities, inventory costs make up a significant proportion of total network costs (Kaminski and Kaya, 2008). Moreover, the optimal inventory policy is not known for SCs with general network structures (Levi and Zhao, 2005). On the other hand, as underlined by Meixell and Gargeya (2005), geographical distances in global situations highly increase transportation costs.

Thus, the following key question arises: Do customer LT constraints in the context of globalization of production activities simply lead to re-think and re-optimize the inventory policies or, more structurally, can impact the design of the SC? We seek to understand the impact of customer LT constraints on the major logistic decisions such as the location of production sites (should they be close to customers to enhance the customer service or located in low-cost countries to reduce costs?), the choice of manufacturing technologies (should they be more automated to shorten the manufacturing LT or less automated to use more labor, especially in low-cost countries?), the selection of suppliers (should the company opt for a distant low-cost supplier or a local supplier with a short lead time ?), etc. Such research questions are motivated by the fact that LT and SC configuration are closely linked. For instance, according to Barnes-Schuster et al. (2006), it is becoming increasingly common that firms relocate closer to their buyers and thereby significantly reduce delivery LT. Meixell and Gargeya (2005) observe that substantial geographical distances in global situations not only increase transportation costs, but complicate decisions because of inventory cost tradeoffs due to increased LTs in the SC.

Hence, beyond the optimization of inventory policies, more structural reflections on the organization of production systems and, more generally, on the design of the whole SC are essential. However, on the one hand, analytical SC models that include LT issues rather focus on operational/tactical decisions in the fields of production-distribution management, inventory management, buyer-supplier management, etc. Such models generally ignore the strategic decisions of location and mission of production sites, selection of suppliers, selection of manufacturing technologies, etc. On the other hand, most existing analytical models for the design of SCs do not consider LTs and, consequently, cannot be used to answer the above relevant questions. Vidal and Goetschalckx (1997), Erenguc et al. (1999), Eskigun et al. (2005), Meixell and Gargeya (2005) and Sourirajan et al. (2007) underline that most network design models in the literature do not consider LT and that LT needs to be considered. Meixell and Gargeya (2005) conclude that global SC design models should have objectives or constraints to evaluate the impact of some important issues such as LT. Overall, most of the LT related literature for SC design tends to be qualitative and conceptual, and has not been subjected to the kind of quantitative analysis that this paper intends to address.

Moreover, most SC design models that include LT only focus on the outbound SC of final products (distribution) and consider a limited number of SC echelons. In addition, such models generally use simple methods to measure LT which mainly focus on transportation LT and ignore purchasing and/or manufacturing LT. Also, they generally ignore supplier selection issues, technology issues, inter-site flows of intermediate products, etc. For instance, Daskin et al. (2002) and Shen et al. (2003) develop location inventory models that incorporate safety stock placement into a location problem for a two-stage network. Eskigun et al. (2005) propose an optimization model for the design of an outbound SC network considering LT, location of distribution facilities and choice of transportation modes. In this model, LT consists in the transit times between the different nodes. Recently, Sourirajan et al. (2007) consider a two-stage SC with a production facility that replenishes a single product at retailers. The main decision is to locate distribution centers in the network. The authors include the replenishment LT at the distribution centers and require the distribution centers to carry enough safety stock to maintain the prescribed service levels at the retailers they serve. An interesting paper in that field is the work by Arntzen et al. (1995). The authors develop a mixed integer program to solve a global SC design problem for an electronics manufacturer. The main decision variables in the model are production, inventory and shipping quantities. LT is measured as the number of days needed for manufacturing and for transit on each link in the SC. However, the authors do not consider suppliers and manufacturing technologies issues among the model decisions and in the determination of LT. Moreover, they include the total LT multiplied by a certain factor α in their objective function, which also contains a total cost multiplied by the factor $(1-\alpha)$. It is not clear, however, how to select the factor α to put together these different entities in the same objective function (Vidal and Goetschalckx, 1997).

In this work, we develop a multi-echelon and muli-product global SC design model that includes customer LT constraints. The customer LT is measured based on the purchasing LT, the manufacturing LT and the transportation LT (between sites and towards customer). We then conduct computational experiments to analyze the impacts of LT on the SC configuration. The proposed model is detailed in section 2. Section 3 is dedicated to the computational experiments and managerial insights. Finally, we give concluding remarks and future research directions.

2 The Model

We consider a multi-echelon SC network with different sets of potential suppliers and potential production (manufacturing and distribution) facilities denoted by S and J, respectively. A single final product is manufactured and delivered to a given customer. We consider the different intermediate products and raw materials that are required to obtain the final product. The set of all involved products is denoted by P. No restrictions are imposed on the number of echelons of the different facilities, on the mission of each facility (manufacturing or/and distribution), and on the transportation links used by the company for shipping its products. In other words, we allow products to be manufactured anywhere and we assume that items can be transported between any types of facilities. Different technologies can be used to manufacture a given product in a given site. The choice of the technology affects the unit production cost and the manufacturing LT. The set of potential technologies is denoted by A. The model is mono-period. We assume that the total customer demand over the planning horizon is known. However, the order quantities may vary from one order to another and are not known with certainty.

We include the LT of purchasing (which depends on the location of suppliers and buyers sites), manufacturing (which depends on the manufactured quantity of the product, the used manufacturing technology and the production facility), transportation (which depends on the location of origin and destination facilities), and delivery (which depends on the location of distribution facility and customer site). The customer LT (the elapsed time between releasing an order and receiving it by the customer) depends on the above different LTs and also on the safety stock held by the firm at different positions of the SC network.

The proposed global SC design model considers the decisions of supplier selection, (manufacturing or/and distribution) facility location, manufacturing technology selection, safety stock positioning and sizing of products flows (from suppliers to facilities, between facilities, and towards the customer). The objective is to configure the SC in order to minimize the total incurred cost while ensuring the ability to meet customer LT constraints.

2.1 Strategic issues

To develop the mathematical formulation of the problem, we introduce a first set of decision variables which are denoted as follows:

- x_{paj} : quantity of product p manufactured in site j using technology a. For all $p \in P$ and $j \in J$, $\sum_{a \in A} x_{paj} = x_{pj}$, where x_{pj} is the total quantity of product p manufactured in site j,

- $z_{p,s\rightarrow j}$: quantity of product p shipped from supplier s to site j,
- $z_{p,j\rightarrow j'}$: quantity of product p shipped from site j to site j',
- h_{pj} : safety stock level of product p in site j,
- $zcus_{p,j}$: quantity of product p shipped from site j to customer. Clearly, $zcus_{p,j}$ is null if p is not a final product,
- y_s : equals 1 if supplier s is selected, 0 otherwise ($s \in S$),
- y_j : equals 1 if site j is open, 0 otherwise ($j \in J$),
- y_{paj} : equals 1 if product p is manufactured in site j using technology a, 0 otherwise.

We use the following notation in referring to the different cost factors of the model:

- OC_j : fixed cost of opening site j (we consider a depreciated cost according to the length of the planning horizon),
- VC_s : fixed cost of selecting and managing supplier s. This cost is generally larger for low-cost suppliers than for other suppliers,
- HC_{paj} : fixed cost of selecting technology a for manufacturing product p in site j. This cost may be large if a fully automated technology is introduced in a developing country.
- IC_{pj} : unit holding cost of product p in site j over the planning horizon,
- MC_{paj} : unit manufacturing cost of product p in site j using technology a,
- PC_{psj} : unit purchasing cost of product p from supplier s by site j. It is important to note that the purchasing cost includes the transportation cost,
- $TC_{pjj'}$: unit transportation cost of product p from site j to site j',
- DC_{pj} : unit delivery cost of product p from site j to customer.

The objective function of the model (1) consists in minimizing the total incurred cost which is the sum of the facility opening cost, the supplier selection cost, the technology selection cost, the purchasing cost, the manufacturing cost, the transportation cost, the delivery cost and the inventory holding cost.

$$\begin{aligned} Min\ \Pi = & \sum_{j\in J} OC_j y_j + \sum_{s\in S} VC_s y_s + \sum_{j\in J}\sum_{p\in P}\sum_{a\in A} HC_{paj} y_{paj} \\ & + \sum_{s\in S}\sum_{j\in J}\sum_{p\in P} PC_{psj} z_{p,s\to j} + \sum_{j\in J}\sum_{p\in P}\sum_{a\in A} MC_{paj} x_{paj} \\ & + \sum_{j\in J}\sum_{j'\in J}\sum_{p\in P} TC_{pjj'} z_{p,j\to j'} + \sum_{j\in J}\sum_{p\in P} DC_{pj} z_{p,j} + \sum_{j\in J}\sum_{p\in P} IC_{pj} h_{pj} \end{aligned} \tag{1}$$

Flow conservation conditions must hold to ensure that the outputs of a given facility j regarding a given product p (sent to the customer and the other facilities of the company and/or consumed for the manufacturing of other products in facility j) correspond to the sum of its inputs for that product (shipped from the suppliers and the other facilities of the company and/or manufactured in facility j). Constraint 2 represents the flow conservation conditions.

$$\begin{aligned} zcus_{p,j} + \sum_{j'\in J\setminus\{j\}} z_{p,j\to j'} + \sum_{p'\in P} \Phi_p(p') x_{p'j} &= x_{pj} + \sum_{s\in S} z_{p,s\to j} + \sum_{j'\in J\setminus\{j\}} z_{p,j'\to j} \\ p &\in P, j \in J \end{aligned} \tag{2}$$

The parameter $\Phi_p(p')$ is defined as the quantity of product p required for the production of a unit of product p'. Constraint 3 guarantees the satisfaction of the customer total demand denoted by D. We recall that $zcus_{p,j}$ is null if p is not a final product. Constraint 4 is relative to the capacity of suppliers where the capacity of supplier s regarding product p is denoted by C_{sp}.

$$\sum_{j\in J} zcus_{p,j} = D \qquad p \in P \tag{3}$$

$$\sum_{j\in J} z_{p,s\to j} \le C_{sp} \qquad p \in P, s \in S \tag{4}$$

We assume that only one technology can be used for the manufacturing of a given product in a given site. This assumption is expressed by constraint 5.

$$\textstyle\sum_{a \in A} y_{paj} \leq 1 \quad p \in P, j \in J \tag{5}$$

Constraints 6, 7 and 8 refer to the logical relationships between the different variables. According to constraint 8, a facility is open if and only if it generates outputs that are pushed towards the customer and/or the other facilities of the company.

$$\frac{1}{\Psi} y_{paj} \leq x_{paj} \leq \Psi y_{paj} \quad p \in P, a \in A, j \in J \tag{6}$$

$$\frac{1}{\Psi} y_s \leq \textstyle\sum_{j \in J} \sum_{p \in P} z_{p,s \to j} \leq \Psi y_s \quad s \in S \tag{7}$$

$$\frac{1}{\Psi} y_j \leq \textstyle\sum_{j' \in J} \sum_{p \in P} z_{p,j \to j'} + \sum_{p \in P} zcus_{p,j} \leq \Psi y_j \quad j \in J \tag{8}$$

2.2 Lead times issues

Now, we turn to modeling LTs. In real-world situations, customer orders are only known few weeks (or maybe few days) in advance which complicates the anticipation of purchasing and production and raises LT issues. In this work, the SC configuration proposed by the model solution must allow for meeting the customer LT constraints in any situation, in particular in the worst case. Let $D^{\max}$ be the maximum quantity that may be ordered by the customer (for any given order) and Δ the elapsed time between the reception of the customer order and the due date of that order (Δ reflects the customer LT constraint). We assume that Δ is similar for all orders. If not, Δ may represent an average value or a minimum possible value to ensure a maximum customer service quality.

Thus, the company must meet the customer orders, whose maximum quantity is $D^{\max}$, within a time limit Δ. This LT constraint can be replaced by a weaker constraint if some information about the customer demand is available before the reception of the order. For instance, if it is known that the order quantity must be larger than a minimum quantity $D^{\min}$, the company can anticipate the preparation of the quantity$D^{\min}$. In this case, the LT constraint that should be considered is rather the obligation of preparing and delivering the quantity $\left(D^{\max} - D^{\min}\right)$ within the time limit Δ. In many real-world situations, such as in the fields of electronic and automotive industry, the customer communicates its demand forecast several weeks before it sends the final order. A partial information about the order quantity is then available. Let $\widetilde{D}$ be the maximum non-anticipated order quantity that should be fulfilled within the time limit Δ (in the above case, $\widetilde{D} = D^{\max} - D^{\min}$). We introduce the following decision variable:

- $\widetilde{\Delta}$: LT required by the firm (from the receipt of the order) to meet the maximum non-anticipated order quantity $\widetilde{D}$.

$\widetilde{\Delta}$ represents the customer LT that can be ensured by the company in the worst case (for the maximum non-anticipated order quantity) and must be smaller than the LT imposed by customer, Δ, as expressed by constraint 9.

$$\widetilde{\Delta} \leq \Delta \tag{9}$$

In our model, $\widetilde{\Delta}$ is a decision variable that depends, on one hand, on the safety stocks held by the company for the different products at different levels and, on the other hand, on the LTs of the activities of purchasing, manufacturing and transportation that are triggered by the receipt of a customer order that induces a non-anticipated quantity $\widetilde{D}$. Thus, we consider the following decision variables:

- $\widetilde{x}_{pj}$: manufactured quantity of product p in site j that is triggered by the receipt of a customer order that induces a non-anticipated quantity $\widetilde{D}$. $\widetilde{x}_{pj} = \sum_{a \in A} \widetilde{x}_{paj}$,
- $\widetilde{z}_{p,s \to j}$: purchased quantity of product p by site j from supplier s that is triggered by the receipt of a customer order that induces a non-anticipated quantity $\widetilde{D}$,
- $\widetilde{z}_{p,j \to j'}$: transported quantity of product p from site j to site j' that is triggered by the receipt of a customer order that induces a non-anticipated quantity $\widetilde{D}$,

- $\widetilde{zcus}_{p,j}$: delivered quantity of product p from site j to customer that is triggered by the receipt of a customer order that induces a non-anticipated quantity $\widetilde{D}$. Clearly, $\widetilde{zcus}_{p,j}$ is null if p is not a final product,
- $\widetilde{y}_{pj}$: equals 1 if $(\widetilde{x}_{pj} > 0)$, 0 otherwise,
- $\widetilde{y}_{psj}$: equals 1 if $(\widetilde{z}_{p,s\to j} > 0)$, 0 otherwise,
- $\widetilde{y}_{pjj'}$: equals 1 if $(\widetilde{z}_{p,j\to j'} > 0)$, 0 otherwise,
- $\widetilde{ycus}_{pj}$: equals 1 if $(\widetilde{zcus}_{p,j} > 0)$, 0 otherwise.

The above variables are used to determine the customer LT, $\widetilde{\Delta}$. To determine their values, and especially the value of $\widetilde{x}_{pj}$, we take into account all available safety stocks (h_{pj}) which implicitly assumes that the firm has enough time to reconstitute its safety stock. These new variables must satisfy the following constraints of flow conservation conditions (10 and 11) and logical relationships (12, 13, 14 and 15). According to constraint 11, the inputs of a given site regarding a given product (quantity purchased from suppliers + quantity shipped from other sites + manufactured quantity + available safety stock) equal the outputs of that product (quantity consumed to manufacture other products + quantity shipped to other sites + quantity delivered to customer).

$$\textstyle\sum_{j\in J} \widetilde{zcus}_{p,j} = \widetilde{D} \quad p \in P \tag{10}$$

$$\begin{aligned}\textstyle\sum_{s\in S} \widetilde{z}_{p,s\to j} + \sum_{j'\in J} \widetilde{z}_{p,j'\to j} + \widetilde{x}_{pj} + h_{pj} &= \textstyle\sum_{p'\in P} \sum_{a\in A} \Phi_p^-(p')\widetilde{x}_{p'aj} \\ &\quad \textstyle+ \sum_{j'\in J} \widetilde{z}_{p,j\to j'} + \widetilde{zcus}_{p,j} \quad p \in P, j \in J\end{aligned} \tag{11}$$

$$\frac{1}{\Psi}\widetilde{y}_{pj} \le \widetilde{x}_{pj} \le \Psi\widetilde{y}_{pj} \quad p \in P, j \in J \tag{12}$$

$$\frac{1}{\Psi}\widetilde{y}_{psj} \le \widetilde{z}_{p,s\to j} \le \Psi\widetilde{y}_{psj} \quad p \in P, s \in S, j \in J \tag{13}$$

$$\frac{1}{\Psi}\widetilde{y}_{pjj'} \le \widetilde{z}_{p,j\to j'} \le \Psi\widetilde{y}_{pjj'} \quad p \in P, j \in J, j' \in J \tag{14}$$

$$\frac{1}{\Psi}\widetilde{ycus}_{pj} \le \widetilde{zcus}_{p,j} \le \Psi\widetilde{ycus}_{pj} \quad p \in P, j \in J \tag{15}$$

One of the novelties of this work in comparison with the existing literature is the use of a more realistic method for calculating the customer LT, $\widetilde{\Delta}$. To obtain $\widetilde{\Delta}$, additional decision variables are required to determine intermediate LTs at different nodes of the SC network:

- $\widetilde{\Delta}cus_{pj}$: LT required to supply the customer from site j with the required quantity of product p triggered by an order that induces a non-anticipated quantity $\widetilde{D}$,
- $\widetilde{\Delta}_{pj}$: LT required to obtain in site j the required quantity of product p triggered by an order that induces a non-anticipated quantity $\widetilde{D}$,
- $\widetilde{\Delta}_{psj}$: LT required to supply site j from supplier s with the required quantity of product p triggered by an order that induces a non-anticipated quantity $\widetilde{D}$,
- $\widetilde{\Delta}_{pjj'}$: LT required to supply site j' from site j with the required quantity of product p triggered by an order that induces a non-anticipated quantity $\widetilde{D}$.

We recall that the above intermediate LTs will serve to calculate the customer LT. We also consider the parameters δ_{paj}, λ_{psj}, $\lambda_{pjj'}$ and λcus_{pj}which respectively represent the unit production time of product p in site j using technology a, the transportation time of product p from supplier s to site j, the transportation time of product p from site j to site j' and the transportation time of product p from site j to the customer. We assume that transportation times do not depend on the transported quantity.

Now, we can formulate the different constraints that allows for obtaining the customer LT, $\widetilde{\Delta}$. Clearly, as given by constraint 16, the customer LT $\widetilde{\Delta}$ corresponds to the LT required for delivering all the required quantity to the customer which may be ensured by several sites. The LT required to deliver the customer with product p from site j ($\widetilde{\Delta}cus_{pj}$) equals the sum of the LT required to obtain product p in site j ($\widetilde{\Delta}_{pj}$) and the transportation time between site j and the customer (λcus_{pj}). This is expressed in constraint 17. We force $\widetilde{\Delta}cus_{pj}$ to be null if $\widetilde{z}cus_{p,j}$ is null which explains the multiplication of the right-hand side of constraint 17 by $\widetilde{y}cus_{pj}$.

The product p can be obtained in site j by different ways: it can either be purchased from suppliers or purchased from another site of the firm or/and manufactured in site

j. The LT required to obtain product p in site j ($\widetilde{\Delta}_{pj}$) is different from one case to another. Constraints 18 and 19 are respectively used to determine $\widetilde{\Delta}_{pj}$ if p is purchased from suppliers or from the other sites of the firm. If product p is manufactured in site j, the LT $\widetilde{\Delta}_{pj}$ must be larger than the sum of the manufacturing LT ($\sum_{a\in A}\delta_{paj}\widetilde{x}_{paj}$) and the LT required to obtain in site j all the input products $p'\in\mathfrak{R}(p)$, where $\mathfrak{R}(p)$ is the set of input products that are used to manufacture product p. This is guaranteed by constraint 20. In this constraint, the LT $\widetilde{\Delta}_{p'j}$ is multiplied by $\widetilde{y}_{pj}$ to avoid taking into account $\widetilde{\Delta}_{p'j}$ if p is not manufactured in site j.

The LT $\widetilde{\Delta}_{psj}$ represents the transportation time of p between supplier s and site j as expressed in constraint 21. Constraint 22 is concerned with the LT $\widetilde{\Delta}_{pjj'}$ which is the sum of the LT required to obtain product p in site j and the transportation time between site j and site j'.

$$\widetilde{\Delta} \geq \widetilde{\Delta}cus_{pj} \quad p\in P, j\in J \tag{16}$$

$$\widetilde{\Delta}cus_{pj} = \left(\widetilde{\Delta}_{pj} + \lambda cus_{pj}\right)\widetilde{y}cus_{pj} \quad p\in P, j\in J \tag{17}$$

$$\widetilde{\Delta}_{pj} \geq \widetilde{\Delta}_{psj} \quad p\in P, s\in S, j\in J \tag{18}$$

$$\widetilde{\Delta}_{pj} \geq \widetilde{\Delta}_{pj'j} \quad p\in P, j\in J, j'\in J \tag{19}$$

$$\widetilde{\Delta}_{pj} \geq \textstyle\sum_{a\in A}\delta_{paj}\widetilde{x}_{paj} + \widetilde{\Delta}_{p'j}\widetilde{y}_{pj} \quad p\in P, p'\in\mathfrak{R}(p), j\in J, j'\in J \tag{20}$$

$$\widetilde{\Delta}_{psj} = \lambda_{psj}\widetilde{y}_{psj} \quad p\in P, s\in S, j\in J \tag{21}$$

$$\widetilde{\Delta}_{pjj'} = \left(\widetilde{\Delta}_{pj} + \lambda_{pjj'}\right)\widetilde{y}_{pjj'} \quad p\in P, j\in J, j'\in J \tag{22}$$

Finally in the constraints below, we force the variables $\widetilde{x}_{paj}$, $\widetilde{z}_{p,s\to j}$, $\widetilde{z}_{p,j\to j'}$ and $\widetilde{z}cus_{p,j}$ to be respectively upper bounded by the strategic variables x_{paj}, $z_{p,s\to j}$, $z_{p,j\to j'}$ and $zcus_{p,j}$ multiplied by the ratio $\frac{\widetilde{D}}{D}$. Indeed, the allocation of products to the different nodes and arcs of the SC network in order to meet customer orders should be adequate with the strategic allocation over the whole planning horizon.

$$\widetilde{x}_{paj} \leq \frac{\widetilde{D}}{D} x_{paj} \quad p \in P, a \in A, j \in J \tag{23}$$

$$\widetilde{z}_{p,s\to j} \leq \frac{\widetilde{D}}{D} z_{p,s\to j} \quad p \in P, s \in S, j \in J \tag{24}$$

$$\widetilde{z}_{p,j\to j'} \leq \frac{\widetilde{D}}{D} z_{p,j\to j'} \quad p \in P, j \in J, j' \in J \tag{25}$$

$$\widetilde{z}cus_{p,j} \leq \frac{\widetilde{D}}{D} zcus_{p,j} \quad p \in P, j \in J \tag{26}$$

3 Lead times impacts and managerial insights

The mathematical formulation of the model is implemented using C++ coupled with Cplex 11.0 (Concert Technology). To be solved with Cplex, the proposed model is first linearized by removing nonlinearities from constraints 17, 20 and 22 using additional variables and linear constraints. In order to conduct our computational experiments, we consider a case study of a company X which manufactures and distributes automotive electrical harnesses for a french automotive constructor located in France. We assume that X has a production site in France (already open) and that managers would evaluate the profitability of partially or totally relocating manufacturing and/or distribution activities to low-cost locations. Three potential low-cost sites are considered in East Europe, North Africa and Asia. The set of potential suppliers can be divided in European suppliers and low-cost suppliers in North Africa and Asia. The total number of suppliers is 10.

The considered final product is the cockpit harness which is composed by different electrical wires, electronic components, plastic components, etc. At an aggregated level, there are 11 purchased products and 8 intermediate products. The total number of products is 19. For each intermediate and final product, two manufacturing technologies can be used: a manual technology or an automated technology. The values of the different costs and LTs are generated based on our experience with the automotive sector while taking into account the disparities between the different locations. The goal of our computational experiments is mainly to analyze the impacts of LT on SC decisions and to deduce some managerial insights. With this scope in mind, we observed the objective function and the main features of the model solution while varying the LT imposed by the customer (Δ).

3.1 Impacts on the total cost

In order to analyze the impacts of LT constraints on the total SC cost, we varied Δ from 0.25 week to 12 weeks and deduced the optimal cost value given by the model as shown in Figure 1.

Figure 1: Optimal cost vs customer lead time

Clearly, the smaller is the LT imposed by customer (Δ) the larger is the total cost. The curve slope is not constant. For instance, increasing Δ from 0.75 to 1 week leads to decreasing the total cost from 5969.16 x10^3 to 5864.48 x10^3 (-1.75%). However, the total cost is only reduced by 6490 (0.11 %) if we increase Δ from 1 to 2 weeks. Such analysis can be very helpful for managers to determine what LT they should offer to their customers and at what price.

3.2 Impacts on the main supply chain decisions

Now, we focus on the impacts of LT constraints on the main SC decisions of facility location, supplier selection, technology choice and safety stock positioning. We first highlight that the considered value of the maximum non-anticipated order quantity $\widetilde{D}$ is 3000; and that the transportation times from France, East Europe, North Africa and Asia to the customer are 0.2, 0.5, 1, and 4 weeks, respectively. In Table 1, we present some features of the model solution for different values of the imposed LT, Δ.

Table 1. Model solutions

$\Delta(week)$	Manufacturing Sites	Distribution Sites	Safety stock of final product
0.25	France, Asia	France	2993 items in France
0.5	France, Asia	France	2965 items in France
0.75	France, Asia	France	2937 items in France
1	North Africa	North Africa	3000 items in North Africa
1.5	North Africa	North Africa	2960 items in North Africa
2	North Africa	North Africa	2920 items in North Africa
3	North Africa	North Africa	2841 items in North Africa
4	France, North Africa	France, North Africa	2366 items in North Africa
5	France, North Africa	France, North Africa	2225 items in North Africa
6	France, North Africa	France, North Africa	2000 items in North Africa
7	France, North Africa	France, North Africa	1791 items in North Africa
8	France, North Africa	France, North Africa	1604 items in North Africa
10	France, North Africa	France, North Africa	1229 items in North Africa
12	France, North Africa	France, North Africa	870 items in North Africa
Without LT	North Africa	North Africa	No safety stock

Observing Table 1, one can first conclude that considering LT constraints has a significant impact on the model solution in general and on the facility location/mission decision in particular. Indeed, the model solution significantly differs from one value of Δ to another and from the cases with LT constraints to the case without LT constraint. This proves the interest of modeling and including the LT constraints in our global SC design model.

In our analysis of the model solutions, we can distinguish between three ranges of the customer imposed LT Δ.

- First range: $\Delta < 1$. The distribution is made by the French site while the manufacturing is ensured by both French and Asian sites. There is no safety stock for several raw materials which are ordered from suppliers following the reception of the customer order. Some quantities of the final product and some intermediate products are held in stock. The majority of intermediate products are manufactured in the Asian site and held in stock in France. There are no inventories in Asia for any of the considered products. It is important to note that some low cost Asian suppliers are selected by the model to supply both Asian and French sites. For $\Delta = 0.25$, the distribution can only be made from France. For $\Delta = 0.5$ and 0.75, the low-cost East European site can be selected for distribution but the model chooses to distribute from France while keeping manufacturing activities in Asia and France. Indeed, the distribution from the French site allows for holding relatively lower safety stocks and avoids spending additional transportation costs.
- Second range: $1 \leq \Delta < 4$. Only the North African site is selected for both manufacturing and distribution. Similarly to the first range, the higher is the value of Δ the lower is the safety stock of final product held by the company. Also, the higher is the value of Δ the higher are the quantities of final and intermediate products that are suggested to be manufactured following the reception of the customer order. Unlike the first case, almost all the purchased products are held in stock since the purchasing LT from suppliers (especially, European suppliers) to the North African site are relatively high. The only exception concerns a component purchased from

a low-cost North African supplier for $\Delta = 3$. Asian suppliers of the first case are here replaced by European and/or North African suppliers.

- Third range: $4 \leq \Delta \leq 12$. Both French and North African sites are selected for both manufacturing and distribution. This result is not predictable since one can expect the model to select the low-cost North African or/and Asian sites. We checked that the selection of the French site leads, on one hand, to a significant decrease in the safety stocks and thus a decrease in inventory costs and, on the other hand, to a decrease in the purchasing costs from European suppliers (we recall that purchasing costs include transportation costs). The production of the final product and most intermediate products in the French site is triggered after receiving the customer order. The selected suppliers are the same as in the second case but the allocation of such suppliers to buyers sites is different. For this third range of Δ, a significant decrease of inventory costs would lead to select the Asian site. Further experiments on this issue may show more interesting results.

Overall, we can conclude that unlike the common belief of some managers, the minimization of costs is not always linked to the selection of low-cost production sites if one takes into account LT constraints and considers the costs of purchasing, transportation, safety stocks, etc. As shown in our computational experiments, the additional costs of transportation and inventory lead, in some cases, to keep origin sites or/and to discard distant low-cost locations. The model often selects the North African site because it offers the best tradeoff between low purchase and production costs and short LT. For all the tested instances, the model selects automated technologies in France and manual technologies in Asia and North Africa. This result can be explained by the manufacturing costs resulting from these technologies. A direct correlation between the choice of manufacturing technologies and the LT constraints does not clearly appear in the performed experiments. Additional experiments should be conducted in that direction while varying the values of manufacturing costs.

4 Conclusion

In this paper, we developed an optimization model for the design of global supply chains while considering lead times constraints. The main decisions of the proposed model are facility location, supplier selection, technology choice, safety stock positioning of purchased, intermediate and final products, etc. The model considers a multi-echelon supply chain and the bill of materials links between the different types of products. To calculate customer lead times, we consider the lead times of purchasing, transportation (inter-sites and towards customers) and manufacturing. The integration of lead times constraints in a global supply chain design model is the main novelty of this work.

We experimentally showed that the consideration of lead times constraints leads to completely changing the configuration of the global supply chain especially regarding facility location, supplier selection, and safety stock positioning. We also showed that unlike the strategy of some managers who close origin sites in developed countries and open delocalized sites in low-cost countries, keeping the origin site may be the best solution in several cases. Overall, we found that selecting a location that offers a good tradeoff between low costs and short lead times is the best solution in many situations.

Clearly, such results should be considered within the limits of our assumptions in both the mathematical formulation of the model and the characteristics of the case study. In our future work, we will focus on improving the modeling of lead times to better reflect realistic situations and expanding our computational experiments to study other cases while varying some key parameters such as global demand and cost factors.

References

Arntzen, B., Brown, G., Harrison, T., Trafton, L. (1995). Global supply chain management at digital equipment corporation. Interfaces 21 (1), 69-93.

Barnes-Schuster, D. , Bassok, Y., Anupindi, R. (2006). Optimizing delivery lead time/inventory placement in a two-stage production/distribution system. European Journal of Operational Research 174, 1664–1684.

Daskin, M.S., Coullard, C., Shen, Z.J.M. (2002). An inventorylocation model: formulation, solution algorithm and computational results. Annals of Operations Research 110, 83–106.

Erenguc, S.S., Simpson, N.C., Vakharia, A.J. (1999). Integrated production/ distribution planning in supply chains: an invited review. European Journal of Operational Research 115, 219–236.

Eskigun, E., Uzsoy, R., Preckel, P.V., Beaujon, G., Krishnan, S., Tew, J.D. (2005). Outbound supply chain network design with mode selection, lead times and capacitated vehicle distribution centers. European Journal of Operational Research 165, 182–206.

Feigin, G. E. (1999). Inventory planning in large assembly supply chains. S. Tayur, R. Ganeshan, M. J. Magazine, eds. Quantitative Models for Supply Chain Management. Kluwer Academic Publishers, Boston, MA.

Hammami, R., Frein, Y., Hadj-Alouane, A.B. (2008). Supply chain design in the delocalization context: Relevant features and new modeling tendencies. International Journal of Production Economics 113, 641-656.

Hammami, R., Frein, Y., Hadj-Alouane, A.B. (2009). A strategic-tactical model for the supply chain design in the delocalization context: Mathematical formulation and a case study. International Journal of Production Economics 122, 351–365.

Hsu, S-L., Lee, C.C. (2009). Replenishment and lead time decisions in manufacturer–retailer chains. Transportation Research Part E 45, 398–408.

Kaminsky, P., Kaya, O. (2008). Inventory positioning, scheduling and lead-time quotation in supply chains. International Journal of Production Economics 114, 276–293.

Levi, D.S., Zhao, Y. (2005). Safety Stock Positioning in Supply Chains with Stochastic Lead Times. Manufacturing & Service Operations Management 7(4), 295–318.

Meixell, M.J., Gargeya, V.B. (2005). Global supply chain design: A literature review and critique, Transportation Research Part E 41, 531-550.

Ouyang, L. Y., Wu, K. S. (1997). Mixture inventory model involving variable lead time with a service level constraint. Computers and Operations Research 24(9), 875–882.

Ozsen, L. (2004). Location-inventory planning models: capacity issues and solution algorithms. Ph.D. thesis, Northwestern University, Evanston, IL.

Vidal, J.C., Goetschalckx, M. (1997). Strategic production distribution models: a critical review with emphasis on global supply chain models. European Journal of Operational Research 98, 1–18.

Shen, Z. M., Coullard, C., Daskin, M. S. (2003). A joint location-inventory model. Transportation Science 37(1), 40–55.

Sourirajan, K., Ozsen, L., Uzsoy, R. (2007). A single-product network design model with lead time and safety stock considerations. IIE Transactions 39 (5), 411–424.

You, F., Grossmann, E.Y. (2008). Design of responsive supply chains under demand uncertainty. Computers and Chemical Engineering 32, 3090–3111.