

Invited Review

Modeling and design of global logistics systems: A review of integrated strategic and tactical models and design algorithms

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Abstract

The overall focus of this research is to demonstrate the savings potential generated by the integration of the design of strategic global supply chain networks with the determination of tactical production–distribution allocations and transfer prices. The logistics systems design problem is defined as follows: given a set of potential suppliers, potential manufacturing facilities, and distribution centers with multiple possible configurations, and customers with deterministic demands, determine the configuration of the production–distribution system and the transfer prices between various subsidiaries of the corporation such that seasonal customer demands and service requirements are met and the after tax profit of the corporation is maximized. The after tax profit is the difference between the sales revenue minus the total system cost and taxes. The total cost is defined as the sum of supply, production, transportation, inventory, and facility costs. Two models and their associated solution algorithms will be introduced. The savings opportunities created by designing the system with a methodology that integrates strategic and tactical decisions rather than in a hierarchical fashion are demonstrated with two case studies.

The first model focuses on the setting of transfer prices in a global supply chain with the objective of maximizing the after tax profit of an international corporation. The constraints mandated by the national taxing authorities create a bilinear programming formulation. We will describe a very efficient heuristic iterative solution algorithm, which alternates between the optimization of the transfer prices and the material flows. Performance and bounds for the heuristic algorithms will be discussed.

The second model focuses on the production and distribution allocation in a single country system, when the customers have seasonal demands. This model also needs to be solved as a subproblem in the heuristic solution of the global transfer price model. The research develops an integrated design methodology based on primal decomposition methods for the mixed integer programming formulation. The primal decomposition allows a natural split of the production and transportation decisions and the research identifies the necessary information flows between the sub-systems. The primal decomposition method also allows a very efficient solution algorithm for this general class of large mixed integer programming models. Data requirements and solution times will be discussed for a real life case study in the packaging industry.

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1. Introduction

In today's rapidly changing world, global corporations face the continuing challenge to constantly evaluate and configure their production and distribution systems and strategies to provide the desired customer service at the lowest possible cost while maximizing their after tax profit. Not only are the geographical and political boundaries changing rapidly due to the formation and/or further strengthening of trade alliances, but also the global corporations themselves constantly merge, acquire, and divest themselves of suppliers, product groups, and customer markets.

Logistics, our term for integrated production and distribution, is one of the factors that tie the different components of a corporation together. The logistics components of a corporation consist of: (1) a number of manufacturing plants, (2) zero, one, or more distribution echelons with distribution centers, (3) the customers, (4) the suppliers of components and raw materials, (5) recycling centers for used products and returned packaging containers, and finally (6) the transportation channels that link all of the above components. Frequently asked questions of logistics engineers and managers are:

- Is it profitable to serve the customers in this country with this product?
- In which plant and in which country should we manufacture this product?
- How should we distribute this product and what transportation modes should we use?
- What is the tactical production plan and how much inventory of which products should we store where?
- What vendors in what countries should we use for this product?
- Our company acquired another organization and needs to merge two production and distribution networks, what is the best configuration?
- What is the most economical and ecological sound way to comply with environmental regulations on recycling and disposal?

When configuring global supply chains, additional complicating factors arise such as duties, taxes, exchange rates, and trade blocks. A corporation might want to "realize" profits in different countries depending on the difference in tax treatments and the possibilities of capital repatriation in those countries. Member countries in a trade block might have duty adjustments when importing goods, if these goods were originally exported from some of the member countries.

Long-range survival for international corporations will be very difficult to attain without highly optimized strategic and tactical global logistics plans. Savings in the 5–10% range, which can be achieved by using strategic and tactical logistics models, can dramatically affect the profitability of the corporation. At the same time, quick responses to immediate logistics questions should be provided consistent with and based on the strategic logistics plan of the corporation.

Too often the answers to these questions are given without much systematic investigation but rather based on previous "intuitive" knowledge. The possibilities for failing to consider a more cost efficient configuration are obvious. Hence, what most companies need is a comprehensive methodology and engineering design method that allows them to rapidly prototype and evaluate several logistics chain configurations. This methodology should also make it easy to pose "what-if" questions or, in other words, to perform interactive sensitivity analyses.

The authors have been working for a number of years on the modeling and design of several variations of these strategic and tactical logistics systems. Models and algorithms for specific systems have appeared previously in the literature. The focus in this manuscript is on the integration and synthesis of the previous research and on the identification of future research directions.

In the remainder of this manuscript, Section 2 provides a review of models and their corresponding solution algorithms for the design of global logistics systems. Section 3 shows the impact of the optimization of transfer prices in glo-

bal logistics. In Section 4, an efficient decomposition algorithm for multiperiod production–distribution networks is presented. Section 5 contains the conclusions and directions for future research.

2. Literature review

2.1. *Mathematical programming models for global logistics systems*

This review focuses on the application of mathematical programming models in the strategic design and improvement of global logistics systems. Global supply chains have known significant exposure in the business journals in the last few years. However, at the current time there does not exist an engineering design methodology to configure supply chains so that they support the long-range logistics vision of the corporation. Vidal and Goetschalckx (1997) identify several lacking features and opportunities for research in the methodology for the strategic and tactical design of global logistics systems. Much of the research ignores relevant international factors such as transportation mode selection, the allocation of transportation cost among subsidiaries, the inclusion of inventory costs as part of the decision problem, the explicit inclusion of suppliers, and the nonlinear effects of international taxation.

There exist many papers on quantitative techniques for the improvement and optimization of supply chains without global considerations, and mixed integer programming models are among the most widely used techniques. Most models address the problem in a regional, local, or single-country environment, where international factors do not have a significant impact on the design of the supply chain. We will also use the term ‘domestic’ to indicate these single-country models.

In one of the earliest papers, Geoffrion and Graves (1974) present an algorithm based on Benders decomposition to solve a multicommodity single-period production–distribution problem. This work is expanded by Geoffrion et al. (1978, 1982), Cohen and Lee (1985), Brown et al. (1987), and Cohen and Moon (1991). More recently, Cole

(1995), Goetschalckx et al. (1994) develop more comprehensive models to optimize single-country supply chains.

Cohen et al. (1989) present the main features that differentiate international supply chain models from single-country models. The most important characteristics identified in the paper are the necessity of treating multinational firms as global systems to obtain economies of scale in order to reduce raw material and production costs, the existence of duties, tariffs, and differential tax rates among countries, random fluctuation of currency exchange rates, and the existence of constraints not included in single-country models, such as local content rules. To consider these characteristics, the authors present a preliminary formulation of a normative model that is a dynamic, nonlinear mixed integer programming (MIP) formulation. The model is nonlinear due to the inclusion of markups for transfer prices and decision variables to allocate overhead costs derived from fixed vendor expenses to plants. The objective function considers the maximization of the firm’s after tax profit. The constraints encompass material supply contracts, bill of materials at plants, market demand, market cash flows, plant capacity, local content rules, and constraints on financial variables. The main contributions of this model are the explicit inclusion of vendor supply contracts and the inclusion of local content constraints. Random fluctuations of currency exchange rates, although mentioned, are not explicitly considered in the formulation. The inclusion of these fluctuations has proven to produce models that are extremely difficult to solve to optimality, even for problems of modest size, as reported in Hodder and Dincer (1986). As a consequence, the authors do not solve their original model. Instead, they present a method to solve a simplified model by fixing the transfer prices and overhead variables. Fixing these variables transforms the model into a more tractable linear MIP model; however, no computational experience is reported. According to the authors, some variants of the model have been successfully developed by them and/or other researchers, but no specific results are presented. Cohen and Lee (1989) present a simplified version of the original model.

Hodder and Dincer (1986) present a mixed integer quadratic programming model that combines plant location variables and product flow variables with financial variables. Although the formulation includes random variables in the objective function representing the sale price of products and the fixed costs at plants, the model is only solved for problems of reasonable size using an approximation procedure.

Cohen and Kleindorfer (1993) describe a normative model framework for the operations of a global company. The model includes the decisions of location, capacity, product mix, material flow, and cash flow features in an international scenario. The model framework consists of a Master Problem, which is a multiperiod stochastic program; a single-period stochastic program subproblem; and a set of submodels that interact with both programs, namely, a stochastic supply chain network model, a financial flow model, a stochastic exchange rate model, and a price/demand model. The authors state that several versions of this model have been implemented and tested, and that research continues with the application of the model in different scenarios. However, no specific mathematical formulations and computational experiences are given. More recently, Arntzen et al. (1995) present a multiperiod, multicommodity mixed integer program to optimize the global supply chain at Digital Equipment Corporation. The objective function considers the minimization of variable production costs, inventory costs, shipping costs, fixed production and production 'style' costs, minus the savings from duty drawbacks and duty relieves. All these terms are weighted by a factor α . The objective function also contains production time and transportation time terms, weighted by a factor $(1 - \alpha)$. These terms are used to model the effects of the "time-to-market" characteristics of the supply chain. Customer demand satisfaction, balance of materials, global BOM, capacity of facilities, system configuration constraints, offset trade and local content, duty drawback restrictions, and bounds on decision variables are included in the set of constraints. The main contribution of this paper is the inclusion – under some assumptions – of offset trade, local content, and duty considerations in an in-

ternational supply chain model that also includes bill of materials (BOM) constraints. The exact method of solution is not fully described in the paper, but the authors claim that using 'non-traditional' methods, such as elastic constraints, row factorization, cascaded problem solution, and constraint-branching enumeration, allow them to obtain impressive results and optimal solutions.

Finally, Huchzermeier and Cohen (1996) develop a stochastic dynamic programming formulation to analyze global manufacturing strategies. Their formulation includes a stochastic exchange rate model, a supply chain network model, and a valuation model. The supply chain model maximizes the after tax profit of the firm, and considers plant capacity and customer demand satisfaction. According to the authors, the main contribution of this model is the inclusion of exchange rate risk in the valuation of global manufacturing strategies. A small example with three countries and five periods is presented as an illustration. No other computational experiences are described in the paper.

The international features of the main models for the design of global supply chain systems are summarized in Table 1. This table has been updated and expanded from the previously published version in Vidal and Goetschalckx (1997).

Geoffrion and Powers (1995) provide an historical perspective on strategic distribution systems design. They report that typical cost reductions range from 5% to 15%. They also state that the process of building a comprehensive logistics model is one of the main benefits since it forces companies to define and understand their logistics functions more accurately. They identify six major changes during the last 20 years. First, logistics has changed from a neglected activity to an essential corporate business function. The concept of the minimization of the total system cost is now widely accepted as the standard logistics objective. A second fundamental change has been the introduction of computers and communications in the logistics operations. The third change was the migration from non-optimizing evaluation, to heuristics, to optimizing using commercially available mixed integer programming solvers. Algorithm acceleration has been based on Benders

Table 1
International characteristics of published strategic logistics models

International characteristics	[1]	[2]	[3]	[4]	[5]	[6]	[7]
<i>Stochastic features</i>							
Exchange rate fluctuation	X	X		X		X	X
Suppliers' reliability							X
Reliability of transportation channels							
Lead times					X		
Stochastic facility fixed costs	X						
Stochastic demand				X		X	
Uncertainty of market prices	X	X		X		X	
Political environment							
Stochastic customer service level							
<i>Taxation and cash flow features</i>							
Taxes and duties	X	X	X	X	X	X	X
Modeling of profit repatriation							
Duty drawback and duty relief					X		
Modeling of transfer prices		X	X				
<i>Non-international features</i>							
Selection of manufacturing technology					X		
Product differentiation by country							
Bill of materials (BOM) constraints		X	X		X		X
Impact of economies of scale	X	X					
Excess capacity determination							
Financial decisions	X			X		X	
Infrastructure modeling			X				
Cash flow modeling				X			
Information flow modeling							
Global supply chain coordination				X			
Modeling of competitors' actions				X			
Modeling of alliances							
<i>Trade barriers</i>							
Quotas	X						
Local content		X			X		
Offset requirements			X		X		
Subsidies	X						

[1] Hodder and Dincer (1986), [2] Cohen et al. (1989), [3] Cohen and Lee (1989), [4] Cohen and Kleindorfer (1993), [5] Arntzen et al. (1995), [6] Huchzermeier and Cohen (1996), [7] Vidal and Goetschalckx (1996).

decomposition, primal network simplex algorithms, and factorization. They observed that Benders decomposition has not become widespread, mainly because it requires a significant technical expertise. The fourth factor has been the growth and use of database tools. The fifth development has been the systematic growth of logistics design models to encompass more features and a larger segment of the supply chain. Finally, the sixth change is the extension of the use of logistics decision support tools by industrial orga-

nizations from focussing solely on warehouse location to supply chain design. They conclude that the future is likely to see a growth in the capabilities of design models and algorithms but that the size of feature requirements by industrial organizations will continue to outstrip the available methodology.

It is clear from the previous results that the incorporation of stochastic elements into the traditional mixed integer programming formulations for supply chain design yields very difficult

formulations. Only for very specific stochastic constraints, such as supplier reliability and on-time performance, can the linear MIP model be extended and remain solvable, as shown by Vidal and Goetschalckx (2000). In the remaining part of this paper, we will describe two significant extensions to the state-of-the-art in logistics models and algorithms.

2.2. *Role and models for transfer prices in global logistics systems*

In this section, we will present a model for the design of global logistics systems that includes the determination of transfer prices. Assuming given exchange rates, the resulting formulation is a bilinear program. We will demonstrate a heuristic algorithm capable of solving problems of real world size.

A transfer price (TP) is the price that a selling department, division, or subsidiary of a company charges for a product or service supplied to a buying department, division, or subsidiary of the same firm, Abdallah (1989). According to O'Connor (1997), "Transfer pricing is the most important international tax issue facing multinationals today, and is expected to remain so for the near future". In his survey of over 200 multinational corporations, 80% of them identified transfer prices as the number one issue they have to face. Most researchers in the operations management area have considered transfer prices a typical accounting problem rather than an important decision opportunity that significantly affects the design and management of a global supply chain. In general, when a logistics analyst attempts to determine the optimal flows of products among facilities, the price of a product is almost always considered a given parameter. The impact of TP policies on taxable income, duties, and management performance is significant. According to Nieckels (1976), small changes in transfer prices may lead to significant differences in the after tax profit of a company. On the other hand, the arbitrary manipulation of transfer prices, such as presented by Cohen et al. (1989), is currently under careful observation by tax authorities and is strictly penalized. Despite these limitations and

based on current regulations, in most of the cases, companies have some range of values for their transfer prices.

Few researchers have addressed the transfer price problem as an integral component of the optimization of a global supply chain. Nieckels (1976) presents a nonlinear mathematical model to determine optimal transfer prices and resource allocation in a multinational textile firm. His formulation includes transfer prices as decision variables and a linear objective function for maximizing the global net income after taxes. The model assumes that the company has a central distribution center from which all products are distributed to the sales subsidiaries and does not include bill of materials constraints. Instead, the problem is formulated as a raw material based model using some transformations of products into raw materials. The transportation costs are always charged to the destination subsidiary.

Nieckel's solution approach begins with a heuristic procedure that assigns initial values to the transfer prices, equal to either their lower or their upper bound. The remaining program is a linear program (LP) that is solved for the optimal flows. Given these flows, the set of transfer prices becomes variable again. To find the new set of transfer prices, a systematic heuristic procedure based on the sign of the derivative of the objective function with respect to the transfer prices is then applied. The solution method iterates between the optimization of the LP and the heuristic procedure to change transfer prices until no further increase in the objective function is possible. According to the author, when the solution procedure stops, a local optimum is found. No upper bound to gauge the quality of the heuristic solution is computed.

More recently, Canel and Khumawala (1997) propose a mixed-integer single-product model for the optimization of a global supply chain. The authors include transfer price decisions in their analysis, but they fix the transfer prices to either their lower or upper bound before solving the model depending on the first derivative of the objective function with respect to the transfer price. Additionally, transportation costs are always allocated to the destination subsidiary. As a consequence, this model does not include the

transfer price problem and the allocation of transportation costs as part of the decision process. They develop two acceleration rules for the branch-and-bound based solution method, which compute profit increases for closing an open facility and for opening a closed facility. In their numerical experiments, this decreases the solution times by a factor of up to 50 compared with the standard MIP solution method of LINDO. For small cases the acceleration rules allowed the solution of the problem at the root node.

3. Models and solution algorithms for the determination of transfer prices in global logistics systems

A simple example will be used to illustrate the fundamental ideas. Fig. 1 shows the supply chain under consideration. Subsidiary *a*, located in country A, manufactures a single product and sells it to subsidiary *b*, located in a different country B. The material flow is represented by *x*, the transfer price by *t*, and the allocation proportion of the transportation cost by *p*. Since tax authorities disallow the use of different transfer prices for the same product to different destinations, the transportation costs must be modeled separately for every combination of origin, destination, and commodity. The allocation proportion *p* models what fraction of the transportation cost each subsidiary will pay for.

Fig. 2 illustrates the corporate tax rate function we consider for all countries. No tax credit for losses is included in the initial analysis. When the corporate tax rate function is more complex, that is, when it has more ‘steps’ and breakpoint values, additional analysis is necessary. However, for large companies the function considered here is realistic and valid in most countries.

To derive the general function of the global Net Income After Taxes (NIAT) in this example, we

should consider four disjoint regions for the Net Income Before Tax (NIBT): both subsidiaries make a profit, only subsidiary *a* makes a loss, only subsidiary *b* makes a loss, and both subsidiaries make a loss. Fig. 3 shows the global NIAT versus the transfer price *t* for different values of the material flow *x*. Obviously, for the NIAT to be bounded, there must exist an upper bound on the flow *x* from *a* to *b*. This bound is determined by a limited capacity of one or the two subsidiaries, by a limited demand, and/or by other flow constraints imposed on the system. Notice that the optimal solution to the problem depends on both, the flow and the bounds on the transfer price: the optimal transfer price may be equal to the lower bound, or to the upper bound, or may fall strictly between them.

The NIAT is modeled traditionally by substituting two nonnegative variables, representing the profit and loss of a subsidiary, for the free variable that represents the NIBT of that subsidiary. In the resulting model, for every flow the product of the transfer price multiplied by the material flow quantity, denoted by *tx*, appears in the two equations that determine the NIBT of the origin and destination country. A verbal description of the model is shown below.

$$\begin{aligned} \text{Maximize global after tax profit (given in} \\ \text{dollars for the time period under analysis)} = \\ \text{After tax profit of internal suppliers} \\ + \text{After tax profit of plants} \\ + \text{After tax profit of DCs} \end{aligned}$$

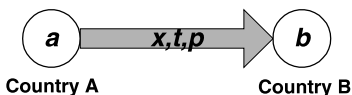


Fig. 1. Two country supply chain schematic.

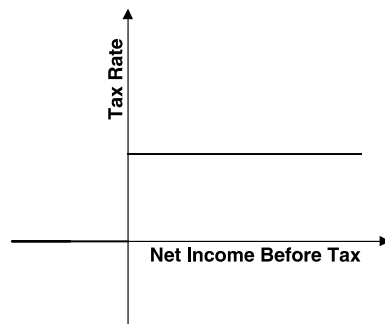


Fig. 2. Tax rate step function.

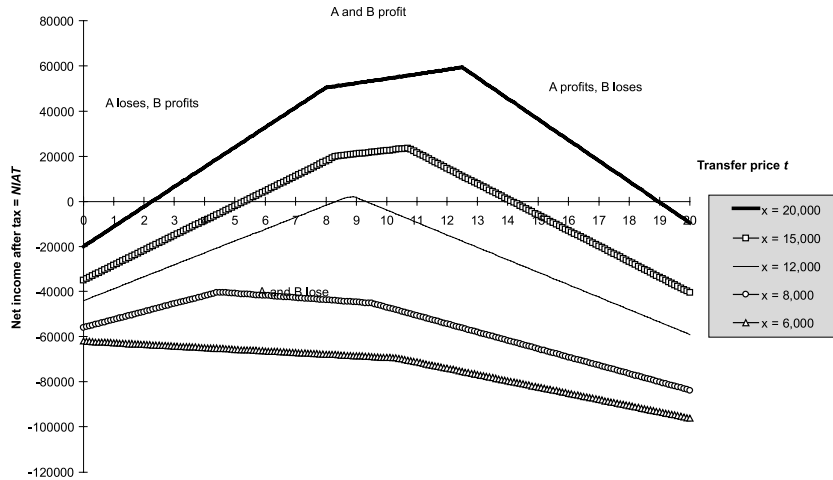


Fig. 3. NIAT for the two country supply chain example.

Subject to: Expressions for the *NIBT* of internal suppliers, plants, and DCs
 Suppliers' capacity (internal and external suppliers)
 Production capacity at plants
 Customer demand constraints
 Bill of materials at plants and balance constraints at DCs
 Minimum profit for internal suppliers, plants and DCs (optional)
 Bounds on transfer prices and general bounds on decision variables

The detailed expression for the net income before tax of distribution centers located in countries where duties are charged on the FOB value is provided in Appendix A as an example. The full model is described in Vidal and Goetschalckx (1998).

This model, denoted as $P(x, t, v, p)$, is a non-convex optimization problem with a linear objective function, a set of linear constraints, and a set of bilinear equality constraints. As such the problem is NP-hard and difficult to solve for large instances. This problem belongs to the more general class of a general bilinear problem having bilinear constraints, as shown in Al-Khayyal (1992). Bilinear programming problems when the con-

vexity of the feasible set is relaxed are more difficult problems to solve (Al-Khayyal, 1990). All computational results reported in the research literature on global and bilinear optimization for this problem correspond to relatively small instances of this problem. However, in global supply chain models, we usually face medium to large-scale optimization problems for which none of these global optimization approaches appear to work satisfactorily. For this reason, and given the structure of the problem, an optimization-based heuristic procedure using successive LP solutions has been developed initially.

The transportation cost allocation reflects the terms of the transaction, which are more precisely defined as INCOTERMS. Some of these are, for example, free on board (FOB), free alongside ship (FAS), and cost, insurance and freight (CIF). It is important to note that the proportion of transportation costs, represented by the variables $propw_{jkm}$ and $prosp_{ijm}$, are allowed to be different from a specific origin to different destinations, using a given transportation mode. This is so because there is more flexibility allowed by the tax authorities to define the subsidiary that pays for the transportation costs and the terms of each transaction. Consequently, the bilinear terms in x and p can be linearized by using the following substitutions:

$$propw_{ijm} \sum_r W_r s_{ijmr} = z_{ijm},$$

$$propw_{jkm} \sum_p W_p x_{jkmp} = z_{jkm}.$$

The rationale for the definition of these variables comes from the fact that the proportions to allocate transportation costs do not depend on the specific component or finished product since these costs are expressed per unit of weight. The resulting problem will be denoted as $P(x, t, v, z)$.

Observe that we cannot use the same approach to linearize the bilinear terms in x and t since the former variables differ from the latter in the sub-index j (for $tpsuple_{ijr}$ and s_{ijmr}), and in the subindex k (for $tppldc_{jkp}$ and x_{jkmp}). As a requirement for the justification of transfer prices to tax authorities, all the transfer prices from a given origin and for a given component or finished product must be the same for all the destinations. The transfer price, of course, does not include the transportation cost, which is modeled separately. This can be thought of as the transfer price being determined based on production costs, and therefore there is no reason to allow it to be different for different buyers. In addition, all transfer price variables have a lower and an upper bound, which reflect feasible markups for production costs and a profit margin, or for possible discounts from market prices.

We can relax the constraint that all transfer prices must be the same from each origin to all destinations for a given raw material (or finished product) by redefining the transfer price decision variables to include the destination facility as follows:

- $tpsuple_{ijr}$ = transfer price of raw material r shipped from supplier i to plant j (not including transportation costs); [monetary units of home country of supplier i /unit of r],
- $tppldc_{jkp}$ = transfer price of finished product p shipped from plant j to distribution center k (not including transportation costs); [monetary units of home country of plant j /unit of p].

By doing this, we are now able to make the following substitutions to linearize the remaining nonlinear terms existing in the bilinear constraints of problem $P(x, t, v, z)$:

$$tpsuple_{ijr} \sum_{m \in T(i,j)} s_{ijmr} = y_{ijr},$$

$$tppldc_{jkp} \sum_{m \in T(j,k)} x_{jkmp} = y_{jkp}.$$

The resulting problem will be denoted as $P(x, y, v, z)$. For the problem $P(x, y, v, z)$ to be equivalent to the original problem $P(x, t, v, p)$, we need to add constraints that ensure that all transfer prices from a given origin to all destinations for a given raw material or finished product are equal. More precisely, these constraints are the following:

$$\frac{y_{ijnr}}{\sum_{m \in T(i,j_n)} s_{ijnmr}} = \frac{y_{ijn+1r}}{\sum_{m \in T(i,j_{n+1})} s_{ijn+1mr}},$$

$$\frac{y_{jknp}}{\sum_{m \in T(j,k_n)} x_{jkmp}} = \frac{y_{jk_{n+1}p}}{\sum_{m \in T(j,k_{n+1})} x_{jk_{n+1}mp}}$$

for all possible combinations of j_n and j_{n+1} , and k_n and k_{n+1} . Evidently, the relaxation of Problem $P(x, y, v, z)$ without the additional constraints provides an upper bound on the original problem $P(x, t, v, p)$. Let us call this relaxed problem $P_R(x, y, v, z)$. This upper bound will be used for establishing the performance of the overall procedure.

Clearly, if we fix the set of variables x in Problem $P(x, t, v, z)$, then the problem becomes linear in t , and vice versa. Thus, we can iterate by successively fixing one set of variables and solving the remaining linear program for the other set. The process can be terminated when the change in the objective function value is negligible. We use the notation $P(x, t, v, z | x)$ and $P(x, t, v, z | t)$ to denote Problem $P(x, t, v, z)$ with fixed flows and with fixed transfer prices, respectively. The difficulty in solving the original problem $P(x, t, v, p)$ to optimality is due to its multi-extremality characteristic, that is, the existence of multiple local optima. Consequently, the local solution obtained by the heuristic procedure is highly dependent on the starting point. We compared several different algorithms for determining the starting point.

The first starting point is generated by the solution of problem $P_R(x, y, v, z)$ and taking the optimal set of flows. A second starting point is generated by taking the solution of problem $P_R(x, y, v, z)$ and taking the optimal set of transfer prices. If the optimal solution to problem $P_R(x, y, v, z)$ contains at least a set of transfer prices that are not feasible, we use the weighted average of all different transfer prices, so that the total amount transferred from the given origin remains constant. If there is no flow from some origins, then we select the lower bound on the transfer price to start the process. The expression for the *NIAT* of the global corporation contains terms of the form $[(1 - TAXA) - (1 - TAXB) (1 + D)]tx$. This suggests that if the expression in the brackets is greater than zero, then the transfer price should be set to its upper bound; otherwise, it should be set to its lower bound. Nieckels (1976) presents the same heuristic to start his solution procedure, as do Canel and Khumawala (1997). We also have examined the behavior of the procedure when setting all the transfer prices either to their lower bound (LB) or to their upper bound (UB). In addition, we allow the procedure to begin with all the transfer prices set to the middle of the interval, that is, equal to $(LB + UB)/2$.

The procedure described in the previous section has been implemented using AMPL and CPLEX. All the experiments have been done on an IBM RS6000 model 590 with 512 MB of RAM. We have conducted extensive computational experiments using diverse starting points and two sets of instances of different sizes. All instances have been carefully generated to approximate the costs and constraints of real instances as much as possible. The main characteristics of these instances are shown in Table 2. Further details can be found in Vidal and Goetschalckx (2001).

Computational experiments with various procedures to determine the starting points yielded optimality gaps less than 2.2% for the medium instance in less than 384 seconds. For most of the instances solved, the best solutions have been obtained when the starting point is either the optimal flows or the optimal transfer prices from the relaxed problem. The iterative procedure tends to quickly converge to a high quality solution and

Table 2

Main characteristics of the small and medium instances solved

Characteristic	Small instances	Medium instances
Total number of suppliers	11	50
Number of internal suppliers	3	12
Number of manufacturing plants	3	8
Number of distribution centers	8	10
Number of customer zones	20	80
Number of components	10	35
Number of finished products	5	12
Average transportation modes/arc	2.8	3.1
Number of decision variables	1544	10,100
Number of constraints	521	2926

then improvements level off. The user can limit the allowed computation time as an alternative stopping criteria.

It should be observed that the user has no control over the achieved optimality gap. If the optimality gap of a solution is unacceptable, the only action a user can take is to try a different starting point heuristic. To overcome this problem, Vidal (1998) developed a global optimization procedure that solves the above problem to within a predetermined optimality gap. To improve the feasible solutions and tighten their upper bounds, a global optimization procedure based on the work by Ben-Tal et al. (1994) was implemented. The particular structure of the problem was exploited to calculate dual bounds and specialized branching rules were implemented. The global optimization procedure improved the feasible solutions and/or tightened the upper bounds in acceptable computation time, showing that the original solutions given by the primal heuristic procedure were closer to optimality than could originally be established.

To measure the impact of the simultaneous determination of the transfer prices and the material flows in the international logistics systems, we compared the results of the following two procedures. The first procedure is the global and integrated optimization procedure described above. The second procedure has several variants, all of which are likely to be used in practice. We assume that each transfer price has an upper and lower bound mandated by the tax authorities of the origin and destination country. The upper and

lower bound should not exceed 10% from the mean so that the company can justify its transfer prices to tax authorities. Assume that the company first sets the transfer prices with one of four policies: mid point of the interval, based on the derivative of the objective function (this heuristic has been described above), at the lower bound, and at the upper bound of the interval. After that the company solves for the optimal material flows to maximize the after tax profit. The savings generated by the integrated procedure as compared with the four hierarchical procedures are given in Table 3. For the five instances of the medium problem instance, the average profit increase was 17.3% and ranged from as small as 0.18% to 95.2%. There was not an a priori characteristic that predicted the savings for a particular instance. Clearly, significant savings could be achieved, depending on the individual logistics systems data, by using the integrated procedure as compared to state-of-the-art hierarchical procedures.

The above model assumed that the location and existence of facilities are known. However, corporations may be interested in determining the optimal configuration of international logistics systems to test the economic feasibility of new configurations and new products. The above procedure for the global logistics system design can be extended to incorporate these configuration decisions. In the above solution procedure, the problem $P(x, t, v, z | t)$ is repeatedly solved as a subproblem. This subproblem can be extended to incorporate binary decision variables corresponding to decisions to open or close a facility. This subproblem exhibits the standard mixed integer linear structure of domestic design models. However, the overall global heuristic and optimal so-

lution procedures require a fast solution method for the subproblem. In Section 4, we will develop such an efficient and effective solution procedure for the domestic subproblem based on Benders decomposition.

4. Models and solution algorithms for the design of multiperiod logistics systems

The location decisions in a domestic logistics model involve the geographical placement and size of the corporate facilities such as the manufacturing plants and distribution centers. We also consider the establishment and size of individual production lines part of the strategic decisions, because of the cost and time involved in moving such a production line. In general, manufacturing companies produce finished goods in multiple stages. Without loss of generality, we considered a manufacturing process consisting of a primary and secondary production phase. For each phase one or more alternative manufacturing lines exist, which differ by their technology or capacity. The manufacturing lines have maximum production capacities expressed in time units, e.g. hours per month. The resource requirement for manufacturing a particular product on a particular production line is known and expressed in hours per ton. Similarly, the constant marginal cost for every combination of product and production line is known.

The different manufacturing and distribution facilities are connected geographically by transportation channels and temporarily by seasonal inventory. At all facility sites, cycle inventories are created by the incoming and outgoing shipment

Table 3
Profit increases using integrated planning versus hierarchical planning

No.	Middle point (Mid_TP)	Heuristic rule (Heu_TP)	All TP set at lower bounds (LB_TP)	All TP set at upper bounds (UB_TP)
<i>Medium instances profit increase (%)</i>				
1	2.40	0.18	0.75	4.06
2	23.22	12.08	17.09	29.22
3	22.59	30.23	39.93	16.24
4	45.63	65.03	95.20	32.05
5	2.29	0.24	0.68	3.90

flows each with its own frequency. Selection of the transportation channels between the facilities is driven by the transportation costs and the pipeline inventory costs. The transportation channels have a throughput capacity expressed in material flow units, e.g. tons per month.

The only customer service constraints considered are the full satisfaction of the seasonal demands of the customers. We assumed that customer demand is deterministic and ignored the impact of safety stocks.

The integrated production–distribution network design problem can be represented by a multicommodity, fixed charge network flow problem. The network has multiple regions in general and four regions in our example (see Fig. 4, copied from Goetschalckx and Dogan (1999)). The first region corresponds to the suppliers or mills in our case study. The second region corresponds to the first phase of the manufacturing process and the third region corresponds to the second phase of the manufacturing process or distribution centers. Finally, the fourth region corresponds to the customers. We will call these regions supplier, primary manufacturing, finishing, and customer regions, respectively. Transportation arcs connect the regions. A schematic

representation of the network for a single period is shown in Fig. 5, copied from Goetschalckx and Dogan (1999).

The arcs between a pair of nodes in the supplier region allows us to model joint product capacity constraints in each of the mills. Each facility in the primary and finishing region is represented by a sequence of four nodes. The arcs between the first and second node allow us to model fixed and variable cost and capacity constraints for the production section of the facility. The arcs between the second and third node allow us to model fixed and variable costs and capacity constraints for individual production lines in the facility. Finally, the arcs between the third and fourth facility allow us to model fixed and variable costs and capacity constraints for the warehousing section of the facility.

Since this a multiperiod problem, the complete network consists of a number of identical planes, with each plane dedicated to a period. The only connections between the parallel planes of the network are the arcs between the nodes associated with the same warehouse in subsequent periods. The overall production–distribution network design problem can be decomposed into two sub-problems. The first subproblem determines the

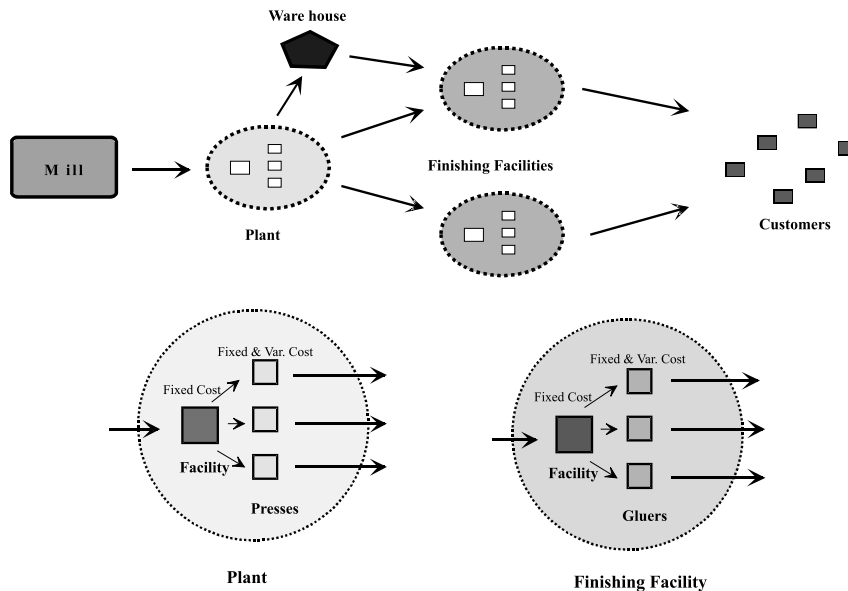


Fig. 4. Overview of the two-stage production–distribution network.

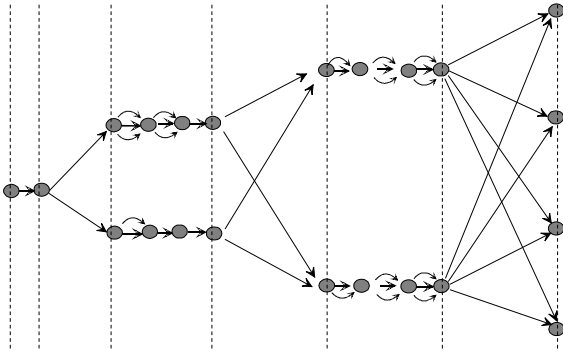


Fig. 5. Single time period network schematic.

resource location and sizing and the production allocation. The second subproblem determines the tactical transportation flows. The verbal formulation of the domestic logistics model is given next.

Minimize: Total cost =
 Supply cost +
 Fixed manufacturing cost +
 Variable manufacturing cost +
 Fixed facility operating cost +
 Variable facility operating cost +
 Warehousing cost +
 Cycle inventory cost at the facilities +
 Pipeline inventory cost +
 Inventory carry-over cost +
 Transportation cost

Subject to: Customer demand satisfaction
 Conservation of flow at facilities
 Conservation of flow at suppliers
 Conservation of flow at machines
 Supplier capacity
 Facility capacity
 Machine capacity
 Single facility type at a site
 Linkage constraints between machines and facilities

The structure of the tactical production–distribution problem leads naturally to a primal decomposition scheme, which was first described by Benders (1962). At each iteration, the mixed integer master problem is solved to obtain a solution that specifies the status of the facilities, the pro-

duction lines, and the production and inventory quantities. The transportation subproblem is then solved to obtain the transportation flows with the lowest costs. This transportation solution is added to the master problem as an additional constraint, and the mixed integer master problem is forced to search for a solution with a lower total cost. This total cost includes the resource allocation plus the transportation costs. The algorithm terminates when the master problem cannot find a solution with a lower total cost; i.e. the master problem has become infeasible. Several acceleration techniques for the decomposition scheme have proven to be very powerful. We applied cut decomposition, cut strengthening through dual variable adjustment, and adaptive optimization of the master problem.

The original primal problem contains the following conservation of flow constraints from suppliers, between the different facilities, and to the customers

$$\sum_{i \in I^t} x_{tps} = s_{tps} \quad t \in T, s \in S^t, p \in P \quad [\alpha] \text{ (supply),}$$

$$\sum_{s \in S^t} x_{tps} = \sum_{l \in L_j} v_{tpjl} \quad t \in T, j \in I^t, \\ p \in P \quad [\beta] \text{ (input stage one),}$$

$$\sum_{k \in J^t} x_{tpjk} = \sum_{l \in L_j} v_{tpjl} \quad t \in T, j \in W^t, \\ p \in P \quad [\gamma] \text{ (output stage one),}$$

$$\sum_{i \in W^t} x_{tpij} = \sum_{l \in L_j} v_{tpjl} \quad t \in T, j \in J^t, \\ p \in P \quad [\delta] \text{ (input stage two),}$$

$$\sum_{k \in K^t} x_{tpjk} = \sum_{l \in L_j} v_{tpjl} \quad t \in T, j \in X^t, \\ p \in P \quad [\epsilon] \text{ (output stage two),}$$

$$\sum_{j \in X^t} x_{tpjk} = D_{tpk} \quad t \in T, p \in P,$$

$$k \in K \quad [\zeta] \text{ (demand),}$$

where x indicate the various flows in the transportation channels; and s , v , and D , indicate aggregate flows from the supplier, aggregate flows

through the facilities at site j of type l , and aggregate flows to customers, respectively. Subscripts t and p indicate the time period and the product. The associated dual variables are shown after each constraint type.

The dual of the transportation problem is expressed by

$$\begin{aligned} \text{Max} \quad & \sum_{t \in T} \left[\sum_{p \in P} \left[\sum_{s \in S^t} \alpha_{tps} s_{tps} + \sum_{j \in W^t} \sum_{l \in L_j} \gamma_{tpj} v_{tpjl} \right. \right. \\ & \left. \left. + \sum_{j \in X^t} \sum_{l \in L_j} \varepsilon_{tpj} v_{tpjl} + \sum_{k \in K^t} \zeta_{tpk} D_{tpk} \right] \right] \\ & - \sum_{t \in T} \left[\sum_{p \in P} \left[\sum_{j \in I^t} \sum_{l \in L_j} \beta_{tpj} v_{tpjl} + \sum_{j \in J^t} \sum_{l \in L_j} \delta_{tpj} v_{tpjl} \right] \right] \end{aligned}$$

s.t.

$$\begin{aligned} \alpha_{tps} - \beta_{tpj} &\leq c_{tps} \quad t \in T, p \in P, s \in S^t, j \in I^t, \\ \gamma_{tpi} - \delta_{tpj} &\leq c_{tpij} \quad t \in T, p \in P, i \in W^t, j \in J^t, \\ \varepsilon_{tpi} - \zeta_{tpk} &\leq c_{tpik} \quad t \in T, p \in P, i \in X^t, k \in K^t. \end{aligned}$$

A disaggregation of the primal cut is obtained by exploring the subproblem structure. The subproblem consists of $|P|$ disconnected networks for each product, which can also be separated into $|T|$ disconnected problems for each season. As it is presented in the dual feasibility constraints, the transportation channels are grouped in three disconnected networks, i.e. from suppliers to first stage production facilities, from first stage warehousing facilities to second stage production facilities, and from second stage warehousing facilities to customers. Using this disconnected networks structure of the subproblem, the primal cut is strengthened by being replaced by $3 \times |P| \times |T|$ constraints. The initial cut is specified by

$$\begin{aligned} & \sum_{t \in T} \left[\sum_{p \in P} \left[\sum_{s \in S^t} \alpha_{tps}^d s_{tps} + \sum_{j \in W^t} \sum_{l \in L_j} \gamma_{tpj}^d v_{tpjl} \right. \right. \\ & \left. \left. + \sum_{j \in X^t} \sum_{l \in L_j} \varepsilon_{tpj}^d v_{tpjl} + \sum_{k \in K^t} \zeta_{tpk}^d D_{tpk} \right] \right] \\ & - \sum_{t \in T} \left[\sum_{p \in P} \left[\sum_{j \in I^t} \sum_{l \in L_j} \beta_{tpj}^d v_{tpjl} + \sum_{j \in J^t} \sum_{l \in L_j} \delta_{tpj}^d v_{tpjl} \right] \right] \\ & \leq Z_0, \quad d \in D. \end{aligned}$$

It can be decomposed into the following three types of cuts:

$$\begin{aligned} \sum_{s \in S^t} \alpha_{tps}^d s_{tps} - \sum_{j \in I^t} \sum_{l \in L_j} \beta_{tpj}^d v_{tpjl} &\leq z_{1tp} \quad t \in T, p \in P, \\ \sum_{j \in X^t} \sum_{l \in L_j} \varepsilon_{tpj}^d v_{tpjl} - \sum_{k \in K} \zeta_{tpk}^d D_{tpk} &\leq z_{3tp} \quad t \in T, p \in P, \\ \sum_{j \in W^t} \sum_{l \in L_j} \gamma_{tpj}^d v_{tpjl} - \sum_{j \in J^t} \sum_{l \in L_j} \delta_{tpj}^d v_{tpjl} &\leq z_{2tp} \quad t \in T, p \in P \end{aligned}$$

and the substitution of the following sum for Z_0 in the objective function:

$$\sum_{t \in T} \sum_{p \in P} (z_{1tp} + z_{2tp} + z_{3tp}).$$

The transportation subproblem exhibits significant primal degeneracy; i.e. there are many dual solutions associated with the primal optimal solution. The selected dual optimal solution has an effect on the strength of the generated cut and hence on the number of cuts needed to prove optimality. If the associated primal flow variable (s , v , D), which is determined by the primal master problem, is zero, then the associated optimal dual variable can be increased (α , γ , ε) or decreased (β , δ , ζ) as long as the dual feasibility constraints remain satisfied without affecting the optimality of the dual solution. However, the adjusted dual variables become larger (α , γ , ε) or smaller (β , δ , ζ) coefficients in the cuts for primal flow variables with a positive or negative sign, respectively, and thus strengthen the cuts when they are added to the master problem.

The seasonal production–distribution model and the associated primal decomposition method described above were tested on a real-life logistics reorganization project of a company that supplies cardboard packages to breweries and soft drink manufacturers. The company ships 12 types of paper products from paper mills, through a two stage manufacturing process, to more than 200 customers around the nation. Both stage one and stage two manufacturing lines are constrained by the available production hours on the machines. Different manufacturing lines can be installed with different processing capabilities and costs for each

product. The demand exhibits a strong seasonal pattern. The production resources required differ significantly from cardboard type to cardboard type and from manufacturing line to manufacturing line. In order to satisfy the peak period's demand, additional manufacturing capacity must be purchased, inventory needs to be built up during the off period, or the company must use subcontractors. The latter option should be avoided if at all possible due to quality concerns.

Initially, the system was configured using the data from a single season. The demands for this season were the peak demands. The season ran from May to July and all costs and parameters were adjusted based on the length of this planning period. The size parameters of the test case and of the resulting mixed integer programming formulation are given in Table 4.

The total running time of a mixed integer programming algorithms depends on the interaction between a variety of factors, such as strength of the integer cuts and linear and integer programming tolerances. The disaggregation of the cuts in the master problem and the strengthening of the dual variables reduced the running times from 865 seconds for a standard implementation of the primal decomposition method to 21 seconds, a reduction by a factor of more than 40.

The multi-season model divided the year into three unequal seasons. The seasons run from January to April, May to July, and August to December, respectively. All costs are adjusted based on the length of the corresponding season. The number of customers was three times as large to

represent the three seasons. For the seasonal model, the cuts are also disaggregated by season. This reduced the solution times further from 1958 to 154 seconds, a reduction by a factor of more than 12. Detailed statistics on the data and the computational experiment can be found in Goetschalckx and Dogan (1999) and Dogan (1996).

Comparing the solution configurations of the one-season and seasonal model showed that inventory was built up during the off-peak periods, which in turn reduced the number of required machines from 19 to 16. The average cost of paper product was reduced by \$20 per ton when inventory buildup was allowed, which yielded approximate savings of \$8.3 million dollars per year. The total cost was approximately \$401 million dollars per year, for savings of 2% versus the best case without inventory. These savings clearly show the importance of integrating tactical production and inventory decisions, when making strategic decisions such as the location of manufacturing plants and manufacturing lines for logistics systems with seasonal demand variances. It should be noted that both configurations are optimal with respect to their respective objective functions and the savings differential is possible only because the multiperiod system has more flexibility. It is expected that the savings of the integrated approach will increase with the size of the variance in the seasonal demand, but additional testing is required to demonstrate this relationship.

5. Conclusions

To remain competitive global corporations need a methodology to evaluate and efficiently configure global logistics systems. While at the current time, there exist several comprehensive models and solution algorithms for the design of strategic single-country or domestic logistics systems, such methodology does not exist for global logistics systems or for systems where strategic and tactical considerations are combined.

One of the most significant issues in global logistics systems is the determination of the transfer prices between subsidiaries of the global corporation. Tax authorities have limited the flexibility to

Table 4
Test case and formulation size parameters

Item	1 Season	3 Seasons
Number of products	12	12
Number of locations	6	6
Number of manufacturing lines	81	87
Number of customers	238	714
Number of transportation channels	1358	3738
Number of nodes	355	1065
Number of arcs	1470	4074
Number of capacitated arcs	88	102
Number of integer variables	88	102
Number of continuous variables	17,640	48,888

set these transfer prices, but at the current time, the prices can still be set within a prescribed interval. We have developed a comprehensive bilinear model to determine optimally the transfer prices within a prescribed tolerance. Computation times are in the order of minutes for realistically sized problems. Making the decisions on transfer prices and material flows simultaneously yield significant after tax profit increases for the corporation when compared to the most sophisticated sequential decision processes.

For domestic logistics systems, we have developed a comprehensive and multiperiod design model. The model is capable of determining the optimal configuration of the logistics system, including which manufacturing lines should be located in which facilities. It also determines the production and inventory schedule for systems with seasonal demands. This mixed integer linear model can be solved efficiently with an adaptation of Benders decomposition. Computation times are in the order of tens of minutes for realistically sized problems. The simultaneous decision on facilities, manufacturing lines, production, and inventory schedules can yield significant savings compared to the sequential decision process where first the facilities are located and then the tactical production–distribution–inventory flows are determined.

At the current time, we are developing a combination of the above models, which will allow the simultaneous optimization of facilities and production–distribution–inventory flows in a global logistics system. It is clear that such a model and solution methodology can yield significant savings for a corporation interested in expanding globally.

A drawback of the above models and solution algorithms is the significant level of technical expertise required to achieve the fast solution times. A very important area of future research is the standardization and technology transfer process of these solution methodologies so that they can be more widely applied. Global corporations are adopting enterprise resource systems at ever increasing rates. The models and methodologies presented here allow these global corporations to use this information in a timely fashion to increase

their profits significantly and to remain competitive.

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Appendix A. Net income before tax expression

The net income before tax, which can be positive or negative, at a distribution center k , located in a country where duties are charged on the FOB value, is defined by the following equation. In general, parameters are denoted in capital letters, while variables are denoted in lower case letters.

$$\begin{aligned}
 & \sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{1}{E_l} \right) MPRICE_{lp} w_{klmp} \\
 & - \sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{1}{E_k} \right) [HANDC_{kp} \\
 & + TRCWM_{klm} W_p] w_{klmp} \\
 & - \sum_{l \in C(k)} \sum_{m \in T(k,l)} \sum_{p \in P} \left(\frac{VP_{kp} H}{E_k} \right) [TTWM_{klm} \\
 & + (CSF_k) SHIPFRE_{Q_{klm}} \\
 & + SSFW_{kp} \sqrt{TTWM_{klm}}] w_{klmp} \\
 & - \sum_{j \in M} \sum_{m \in T(j,k)} \sum_{p \in P(j)} \left(\frac{1}{E_j} \right) [tppldc_{jp} (1 + DUTY_{j kp}) \\
 & + (1 - propw_{jkm}) TRCPW_{jkm} W_p] x_{jkmp} \\
 & - \left(\frac{1}{E_k} \right) FIXDC_k \\
 & = ibtwf_k^+ - ibtwf_k^-, \quad k \in W^f.
 \end{aligned}$$

$CSF_k =$	cycle stock sharing factor at distribution center k , expressed as a percentage between 0 and 1 and indicating the aggregate storage required compared to the sum of the storage required by the individual commodities	$VP_{kp} =$	and destination facility l with transportation mode m unit value of commodity p in home country of facility k
$DUTY_{jkp} =$	import duty for a unit of commodity p imported from the home country of plant j into the home country of distribution center k	$W_p =$ $ibtwf_k^+, ibtwf_k^- =$	unit weight of commodity p net income or loss before taxes of distribution center k
$E_l =$	exchange rate of the country in which customer or facility l is located	$propw_{jkm} =$	proportion of the transportation cost between plant j and distribution center k over transportation mode m paid by the origin plant j
$FIXDC_k =$	fixed cost of distribution center k per time period	$tppldc_{jp} =$	unit transfer price for commodity p from plant j
H	holding cost (monetary unit per monetary unit per time period)	$w_{klmp} =$	number of units of commodity p flowing from distribution center k to customer l over transportation mode m
$HANDC_{kp} =$	unit handling cost of commodity p in distribution center k	$x_{jkm} =$	number of units of commodity p flowing from plant j to distribution center k over transportation mode m
$MPRICE_{lp} =$	market price of commodity p in home country of customer l		
$SHIPREQ_{klm} =$	shipping frequency between origin facility k and destination facility l with transportation mode m		
$SSFW_{kp} =$	safety stock factor for commodity p at distribution center k depending on the customer service requirements of delivery out of stock		
$TRCPW_{jkm} =$	transportation cost per unit weight from plant j to distribution center k by transportation mode m		
$TRCWN_{klm} =$	transportation cost per unit weight from distribution center k to customer l by transportation mode m		
$TTWM_{klm} =$	transportation transit time between origin facility k		

The full model for the determination of transfer prices and transportation cost allocation can be found in Vidal and Goetschalckx (1998).

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