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Design of Global Supply Chains under Uncertainty

by
Behnaz Saboonchi

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ABSTRACT

This research aims at providing managers with a practical decision support tool for the design of global supply chains. The model encompasses the design of a multi-period, multi-stage global supply chain consisting of manufacturing sites, distribution centers and customer zones situated at both domestic and international locations, with uncertain demand. The impacts of exchange and tariff rate variations and the presence of economies of scale in production which lead to different tactical level decisions, capacity expansion, and outsourcing policies are considered.

A two-stage stochastic programming method is used to solve the stochastic mixed-integer nonlinear optimization model, allowing both continuous and discrete stochastic variables. The multiple objectives of minimizing the total cost and maximizing the expected service level are tackled using the ε-constraint method. A heuristic method is proposed to tackle the production, outsourcing and capacity expansion decisions for a special case of the model. The model is finally analyzed through examples to demonstrate its applicability in facilitating decision making for the managers.

DEDICATION

To my family.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude and appreciation to Dr. Guoqing Zhang my supervisor, for his invaluable guidance throughout the course of this thesis work. Special thanks to Dr. Reza Lashkari and Dr. Francis Rieger for their expert guidance and constant support throughout my study. I also sincerely appreciate my family for their endless support and my friends for their help and friendship.

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1. Introduction

1.1. General Overview

With increased competition among different industries, increased customer expectations in terms of quality, price and delivery time, expanding product variety and short product life cycles, offshore sourcing and global supply chain management have turned into unavoidable options for managers. Global supply chains have emerged as one of the major approaches to gain competitive edge and the movement of the domestic supply chains towards globalization involves the company's worldwide interests and necessitates a unified way of managing and coordinating activities all across the globe.

In global supply chain management it is very important to consider the overall costs of the network. While local labor costs may be significantly lower across the border, companies must also consider other factors such as exchange and tariff rates, costs of space, governmental considerations and global trade issues. Lead time management is another important issue since the productivity of the overseas employees and the extended shipping times can either positively or negatively affect the company's lead time, and either way these issues need to be figured into the overall planning.

Risk mitigation is increasingly receiving consideration by companies designing a global supply chain. Moving into international markets necessitates aligning with several uncertainties such as natural disasters, weather conditions, exchange and tariff rates variations, changes in the product demand, etc. Not paying adequate attention to the embedded risks and uncertainties within the global supply chains, might lead to severe failures. At stake are billions of dollars in stock market capitalization, market-share losses from failed product launches, or even the possibility of the whole business failure. LogisticsTODAY [52] ranks the Top Ten supply chains of 2005, and in order to illustrate the influence of global supply chain management and the importance of precise forecasting, mentions the failure story of FEMA (Federal Emergency Management Agency), and the success story of Wal-Mart in response to Hurricane Katrina.

To conclude, in order to survive or remain successful in the today's volatile competition and market conditions, industries should go more towards globalization, and that's exactly what real business practices by top Fortune 500 companies suggest. There exists a vast number of opportunities for research in this area which should definitely go hand in hand with the research on how to model the involved uncertainties, since ignoring the stochastic factors in global supply chains, jeopardizes the applicability of the proposed frameworks.

1.2. Proposed research

1.2.1. Motivation and objectives

As a result of the increasing trend of industries to go towards globalization, research in global supply chain management is also receiving more and more attention. The main motive of choosing this research topic was to get more insights into the issues involved in multinational corporations and the several additional factors that should be taken into account, comparing to the typical domestic supply chains.

The proposed model in this thesis considers the exchange and tariff rates which are the deciding factors in selecting the most appropriate locations across the globe for investments, or choosing the right partners for outsourcing operations. Meixell et al. [30] mention that although most models tackle a difficult feature associated with globalization, few models address the *practical* global supply chain design. We believe a practical and useful model is the one that is flexible enough to address lean and agile supply chains [46] in which the winning criterion is cost and the service level respectively[12]. In our model this is done by considering multiple objectives of minimization of costs and maximization of the expected average service level for all the customers during the planning periods, to act as a tool to adapt the model for both kinds of markets in which the winning criterion is lower costs, and the kind in which the key to success is higher service level [12]. Another feature that makes the proposed model more practical is that the model has the ability of choosing different transportation modes with different lead-times, allowing the decision maker implement the company's policies regarding faster or slower shipments which lead to higher or lower service levels.

Based on the literature review, another issue that has not received enough attention in this research area is the uncertainty factor. Schmidt and Wilhelm [39] and Santoso et al. [37] mention that few studies have addressed the uncertainties associated with global networks. Uncertainties are the integral parts of global companies, for instance exchange rate and economic condition variations directly address the financial performance of supply chains by influencing the procurement or outsourcing costs, and thus affecting the timing of placing orders and purchases, or the outsourcing volumes [8] and [9].

The literature survey in [30] mentions that the researches conducted between 1991 and 1995, mainly considered the variability and uncertainty in exchange rates as the uncertain parameters and some introduced objectives other than cost and profit such as the activity duration, which was used as a performance measure. In the period between1996 to 2000, almost the same factors were considered with more attention to the transfer price and supplier selection decisions. Finally, the literature after 2000, expanded the methods used to tackle these problems, developing network equilibrium models and multi-phase approaches to solve the problems.

Failing to incorporate these factors in any model trying to tackle global problems, may result in great financial losses or even failure of the business and these were our main motives to study the "*Design of Global Supply Chains under Uncertainty*".

1.2.2. Outline of the proposed research

This research is aimed at extending the existing domestic supply chain models to the global context, and models a multistage, multi-period, single-product global supply chain under uncertainty consisting of manufacturing facilities, distribution centers and customer zones.

The objectives considered in the model are minimization of costs and maximization of expected average service level, which are the tools to adjust to the model to different types of supply chains. Based on the ε-constraint method which we have used to solve the multi-objective problem, one the objectives is kept as the main objective and the other performance measures or objectives are added to the problem constraints bounded by some minimum or maximum accepted levels. Of-course in our model any one of the objectives can be conveniently kept as the main, and the other one as a constraint, based on the decision maker's policy.

Inventory and transportation mode decisions are also considered, which are of-course affected by the objective functions, the minimum accepted expected service level and the importance of faster or slower shipments, leading to shorter or longer lead-times.

Customers are assumed to have stochastic demand. The model supports both lost sales and overstocking, depending on the respecting costs and penalties, type and importance of the products or customers or any other policies or considerations the company might follow.

The Two-stage stochastic programming method that is widely used in the literature, is pursued in this research with two approaches: The first approach tackles the problem in case the continuous uncertain variables (demand in our case) follow known probability distributions (Distribution-based approach), and the second approach assumes there is not enough information available about the probability distributions of the stochastic variables, but based on historical data several scenarios with known probabilities can be generated which help address the uncertainties in the model (Scenario-based approach).

1.3. Organization of the thesis

In the next chapter we review the related literature in terms of three categories of "General deterministic supply chain design", "Stochastic supply chain design and solution approaches" and "Global supply chain design". Then in Chapter 3 we describe and develop the proposed model and explain the solution methodology in details. In Chapter 4 we propose a heuristic method to solve a special case of the model and provide an analytical model to obtain managerial insights on production, outsourcing and capacity expansion decisions and then we perform several sensitivity analyses based on numerical examples. Finally in Chapter 5 we make the conclusions, and outline the contributions of this thesis in the global supply chain design research area, and the possible future avenues of research pertaining to this work.

2. Literature Review

In this chapter the related literature has been reviewed under three main categories: General deterministic Supply Chain design, Stochastic Supply Chain design and solution approaches, and Global Supply Chain design.

2.1. General deterministic supply chain design

There is sufficient literature on both the solution procedure and the modeling of different supply chains for different types of products. It ranges from operational level decisions such as the inventory and scheduling problems to rather midrange and strategic ones.

Pirkul and Jayaraman [33] introduce the PLANWAR model as a new formulation to the multi-commodity, multi-plant, capacitated facility location problem. They from a MIP model and provide an effective heuristic solution procedure to solve this supply chain management problem.

They then continue their work in Jayaraman and Pirkul [22] and tackle the strategic and operational decisions in a multi-stage supply chain. They propose a heuristic solution procedure which utilizes the solution generated from a Lagrangian relaxation of the problem. A real-world example is given to illustrate the efficiency and effectiveness of the solution procedure and they finally suggest considering multi-type multilevel distribution centers as an extension to the model.

Wang et al. [47] use supply chain operations metrics (SCOR) as the decision criteria and then employ an integrated analytic hierarchy process (AHP), and preemptive goal programming (PGP) based methodology to consider both qualitative and quantitative factors in supplier selection. Finally a hypothetical case study is presented to show how capacity constraints can be considered by using the AHP final ratings as PGP coefficients.

As previously mentioned, one of the most important characteristics that any practical supply chain model intending to solve real life problems should possess is adaptability to various possible situations. Vonderembse et al. [46] describe a typology for designing different types of supply chains with different products and customers characteristics. The classification based on product types: standard, innovative or hybrid, and product life cycle stages: introduction, growth, maturity and decline, is shown in Figure 1 . Finally case studies of firms are given to better understand the relationships of the three types of supply chains: lean, agile and hybrid.

Product Type **Product Life Cycle**	**Standard**	**Innovative**	**Hybrid**
Introduction	Lean Supply Chain	Agile Supply Chain	Hybrid Supply Chain
Growth			
Maturity		Hybrid/Lean Supply Chain	
Decline			

Figure 1 Supply chain classification based on product type and product life cycle [46]

The agility paradigm had come into place in the early 1990s as an approach to gain competitive advantage, but is now recognized as a winning criterion if not a basic strategy for survival. It basically means using market knowledge and a virtual corporation to exploit profitable opportunities in a *volatile* market place whereas leanness means developing a value stream to eliminate all waste, including time, and to ensure a *level* schedule [32] and [21].

Christopher [12] mentions that "market qualifiers" are the market entry factors, whereas the "market winners" are the market winning criteria. Figure 2 illustrates the differences between the market qualifiers and market winners in the lean and agile supply chains [27].

	Market Qualifiers	**Market Winners**
Agile Supply Chains	Quality Cost Lead-time	Service level
Lean Supply Chains	Quality Lead-time Service level	Cost

Figure 2 Market winners and market qualifiers for agile vs. lean supply chains [27]

Yeh [49] considers a multi-stage supply chain network design problem and develops a memetic algorithm combined with the genetic algorithm (GA), a multi-greedy heuristic method (GH), three local search methods, the Fibonacci number procedure and the linear programming technique to improve the traditional GA, in order to find the lowest cost of the physical distribution flow.

In another recent work Boyaki and Ray [7] develop an analytical framework to study differentiation strategies in supply chains selling two variants of products (regular and express) in terms of price, lead-time and lead-time reliability. First they complement two modeling frameworks previously mentioned by Boyaki and Roy [6], and then discuss the third case where an existing regular product is assumed in the market place, and an express variant to be introduced to the market. Finally they study the behavior of the optimal decisions for the three models under different capacity costs and market structures.

2.2. Stochastic supply chain design and solution approaches

2.2.1. Stochastic supply chain design

There exist several stochastic factors in today's supply chains. Most of the researches that address the uncertainties use two distinct approaches: probabilistic approach, or scenario planning approach. The choice of the most appropriate strategy is very dependant on the context and the extent of available data [50].

Cheung and Powell [10] review the algorithms to solve different types of stochastic distribution problems. They then mention that the newsboy problem may not apply to some situations where consolidation facilities are involved and thus a two-stage stochastic programming method should be considered. Solution approaches are presented for the Tree and Network resource problems and finally the Multi-stage planning is described where the decisions should be made over time.

Sox and Muckstadt [41] provide a formulation and solution algorithm for the finite-horizon capacitated production planning problem with random demand for multiple products. In order to handle realistic-sized instances of the model, they use the Lagrangian relaxation and develop a sub-gradient optimization algorithm. They propose extending the model to the more complicated case of multi-echelon distribution or assembly structures.

McDonald and Karimi [28] present a two-part series of papers on production planning and scheduling models. Part 1 deals with multi-period midterm planning models where optimal allocation of assets to production tasks in order to satisfy the fluctuating demands of the global marketplace is the main goal. The plan performance is assessed relative to an objective function involving maximization of earnings and minimization of production, inventory, and transportation costs. They show that the multi-period model becomes inadequate when the time scale of the planning period is much less than the length of an individual production event. This supplies a natural stepping stone to part 2 of the series.

McDonald and Karimi [29] in part 2 discuss the application of two short-term scheduling formulations of a single-stage, multi-product, and multi-processor facility.

A continuous time formulation is developed for the scheduling problem where the goal is to minimize the production, inventory, and transition costs for a single facility.

Gupta and Maranas [17] propose a two-stage, stochastic programming approach for incorporating demand uncertainty in multi-site midterm supply-chain planning problems adopting the midterm planning model of McDonald and Karimi [28] as the reference model. The inner optimization problem is resolved by obtaining its closed-form solution using linear programming (LP) duality. Computational requirements for the proposed methodology are shown to be much smaller than those for Monte Carlo sampling. Extension of this work is to account for a general probability distribution and to incorporate the uncertainty in revenue, transportation and penalty costs, etc.

Mirhassani et al. [31] consider two modeling approaches to handle practical applications of supply chain network planning problems under uncertainty. The first involves scenario analysis of the solutions to "wait and see" models and the second involves a two-stage integer stochastic programming (ISP) representation and solution of the same problem. They use a parallel Benders algorithm to solve the master problem, and propose using Lagrangian method or parallel branch and bound instead, as a future investigation.

Tsiakis et al. [44] consider the design of a multi-product, multi-echelon supply chain and determine the capacity and location decisions. They consider economies of scale in production costs and in the first case study assume deterministic product demand. In the second case they use two-stage stochastic programming and assume three possible product demand scenarios to model the uncertainty in demand.

Bowonkim et al. [5] consider a network of suppliers and manufacturers facing uncertain market demand. They develop an iterative solution algorithm taking into account both the manufacturer's and the suppliers' capacity. They propose considering multiple periods, joint production mix decisions and joint demand distributions as future research.

Kouvelis and Milner [23] provide a conceptual framework to study the interplay of demand and supply uncertainty in capacity and outsourcing decisions in multi-stage supply chains. They characterize the investment decisions for the single and multi-period versions of the model and focus on how changes in supply and demand uncertainty affect the extent of outsourcing. Finally they show that as the responsiveness of the market to the firm investments increases, the reliance on outsourcing generally increases, and while demand variability increases outsourcing, supply variability decreases it.

Gupta and Maranas [18] provide an overview of Gupta and Maranas [17]. In the proposed bilevel-framework, the trade-off between customer satisfaction level and production costs is captured, and the key features are the capacity constrained production equipment, carry-over of inventory and customer backlogs. The features of the proposed framework are highlighted through a supply chain planning case study.

Chen and Lee [11] propose a scheduling model to deal with multiple goals for a multi-echelon supply chain network with uncertain market demands and product prices. The uncertainty is modeled as a number of discrete scenarios with known probabilities, and the fuzzy sets are used for describing the sellers and buyers preference on product prices. The conflicting objectives are fair profit distribution among all participants, safe inventory levels, maximum customer service levels, and the robustness of the decisions.

Guillen at al. [16] tackle the design problem of a multi-stage supply chain and in order to take into account the effects of uncertainties, a two-stage stochastic model is constructed. The SC configurations obtained by means of deterministic mathematical programming are compared with those determined by different stochastic scenarios, which help consider the effects of uncertainties as the risks associated to the NPV of the investment that has been introduced as an additional objective into the model. The financial risk associated with the different design options results in a set of Pareto optimal solutions that can be used for decision-making.

Santoso et al. [38] integrate the sample average approximation (SAA) scheme and accelerated Benders decomposition algorithm to quickly compute solutions for large-scale stochastic supply chain design problems and use the scenario-based approach to handle uncertainties. Finally they provide empirical results for the design of two realistic supply chain networks and demonstrate that the candidate solutions in an expectation sense, result in significantly smaller cost/cash flow variability, specially in case of higher variability in the uncertain environment, comparing to mean-value problems.

Chan et al. [11] focus on the optimization of the order due date fulfillment reliability in multi-echelon distribution networks with stochastic lead-time and due dates. A multi-criterion genetic integrative optimization methodology is developed which integrates genetic algorithms with analytic hierarchy process to enable multi-criterion optimization, and probabilistic analysis.

Fewer researches address multiple objectives in their model. Typical objectives besides cost minimization and profit maximization are fair profit distribution, safe inventory levels, and maximum customer service levels.

2.2.2. Solution approaches for stochastic supply chain problems

Based on Rosenhead et al. [36] the decision making environments are either (1) certain, where all parameters are deterministic and known; (2) risky, where the values of uncertain parameters follow known probability distribution functions; and (3) uncertain, where there is no information on hand about the probabilities of the uncertain parameters. Problems in risk situations are known as *stochastic optimization problems* whereas the problems under uncertainty are known as *robust optimization problems.*

Snyder [40] provides a very comprehensive literature review on stochastic and robust facility location models. He illustrates both the robust and stochastic approaches for optimization under uncertain and risky environments in the literature and their application to facility location problems. He finally concludes that there exists the lack of successful application due to the cumbersome data requirements for real life stochastic models and then propose four research avenues for the today's operations research technology: (1) Exact algorithms for minimax problems, (2) Multi-echelon models, (3) Stochastic programming technology and (4) Meta-heuristics for general problems.

Two-stage stochastic programming method is widely used in the literature [10], [11] [16], [17], [18], [31], [38] and [44]. Based on the stochastic programming community homepage [54], "The most widely applied and studied stochastic programming models are two-stage programs. Here the decision maker takes some action in the first stage, after which a random event occurs affecting the outcome of the first-stage decision. A recourse decision can then be made in the second stage that compensates for any bad effects that might have been experienced as a result of the first-stage decision. The optimal policy from such a model is a single first-stage policy and a collection of recourse decisions (a decision rule) defining which second-stage action should be taken in response to each random outcome." In other words, in two-stage stochastic programming method the decision variables are separated into two stages. The first-stage decisions are here-and-now type of decisions which are made prior to the stochastic variables' realization, whereas the second-stage decisions are wait-and-see type of decisions which are made after the realization of the uncertainties.

2.3. Global Supply Chain Design

Hodder and Jucker [20] tackle the international plant location problem under price and exchange rate uncertainty for a mean-variance decision maker. They redefine the profit maximizing objective function using the decision maker's risk aversion coefficient and provide an analytic framework to solve the mixed integer quadratic programming problem. The model considers deterministic conditions and does not consider multiple objectives or stages in the supply chain design.

Lee et al. [25] and [26] describe the decision support that manufacturing managers at Hewlett-Packard (HP) require in managing their material flows in their supply chains. They developed an inventory model that the HP's Desk-jet printer division used to evaluate alternative processes and product designs for localization. They finally conclude that localization is an important strategy for success in a global environment.

One of the most comprehensive models by Arntzen et al. [2] presents a multi-period, multi-commodity mixed integer program to optimize the global supply chain at the Digital Equipment Corporation. The terms in the objective function which consist of variable production, inventory and shipping costs plus the fixed costs minus the savings from duty drawbacks and duty relieves, are weighted by some coefficients without mentioning how to calculate them. The model is deterministic and does not consider the service level factor.

Mohamed [51] proposes a model that considers production and logistics decisions for multi-national companies. The decisions made are sensitive to inflation and exchange rates, capacity levels and the efficiency of the plants. It does not consider the stochasticity in demand or in other factors involved in multi-national environments and considers only the minimization of costs as an objective.

A comprehensive literature review on strategic, tactical and operational aspects of international logistic networks is presented by Schmidt and Wilhelm [39]. They discuss the relevant modeling issues for each of the aspects and mention that few studies have addressed the uncertainties associated with tactical aspects of the global logistics networks and there is the need for an approach that unifies all the three planning levels coupled with efficient solution approaches that can solve realistic instances of the models.

Syam [42] decomposes the multi-period capacitated location problem into sub-problems, and uses a Lagrangian based heuristic to calculate both upper and lower bounds on the optimal objective value of the model. Finally the risk-versus-cost trade-off is made by defining risk, and showing that counter intuitively the regions with lower risks and higher costs tend to have lower total costs. This model does not consider the global factors and works under deterministic conditions.

Goetschalckx et al. [14] 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. They analyze two types of problems, one in global and the other one in a domestic context, and then use a heuristic iterative solution algorithm which is capable of solving realistically sized problems.

Transfer price 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 [1]. Vidal and Goetschalckx [14], [45] 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. They mention that transfer pricing is one of the most important issues today's multinational companies face.

Bhutta et al. [3] extend the previously published models on multinational corporation facility location problems specially [51], and incorporate production, distribution, and investment decisions. The model does not consider the uncertainties present in multinational environments.

Meixell et al. [30] review the decision support models for the design of global supply chains. They mention that although most models tackle a difficult feature associated with globalization, few models address the practical global supply chain design. As a future research they recommend considering multi-tier supply chains with internal production sites and external suppliers, more performance criteria and a wider variety of industries.

A group of global supply chain models address the relevant issues and considerations for the business environment under NAFTA. A comprehensive model that provides a decision support aid for the strategic design of an assembly system under NAFTA is by Wilhelm et al. [48]. The model differs from other similar models in that it deals with typical international issues such as domestic-content rules, border crossing costs, transfer prices, income taxes and exchange rates, as well as specific features to the US-Mexico business environment. They propose devising efficient solution procedures to solve large-scale instances of the model as a future research. The model only considers maximization of after tax profit under deterministic conditions.

Bookbinder and Fox [4] obtain the optimal routings for intermodal containerized transport from Canada to Mexico with the associated transportation costs for two transportation modes and the respecting lead-time. In another recent work, Robinson and Bookbinder [35] formulate and solve a mixed-integer programming model to find the optimal supply chain for a real world problem of a Canadian manufacturer of power supplies. Again the model only considers minimization of costs under deterministic conditions.

Goh et al. [15] present one of the few stochastic global supply chain models using multi-stage stochastic programming method. They consider the scenario-based approach to model the discrete uncertain parameters and the related risks. They finally propose a solution procedure to solve the problem with profit maximization and risk minimization objectives. A brief comparison of the features of the key reviewed papers with the proposed model in this research is illustrated in Table 1.

Table 1 Comparison of the key papers and the proposed model

Reference	**Key paper**	**Proposed model**
Hodder and Jucker [20]	➢ Deterministic ➢ Single-stage supply chain ➢ Single objective problem	➢ Stochastic ➢ Multi-stage supply chain ➢ Multi objective problem ➢ Considers tariff rates and transfer prices ➢ Economies of scale present in production ➢ Considers capacity expansion decisions ➢ Enables adjusting different service levels for each customer ➢ Considers different transportation modes with different lead-times
Arntzen et al. [2]		➢ Stochastic ➢ Multi objective problem

	➢ Deterministic ➢ Single objective problem ➢ Considers duty drawbacks	➢ Considers tariff rates and transfer prices ➢ Economies of scale present in production ➢ Considers capacity expansion decisions ➢ Enables adjusting different service levels for each customer
Mohamed [51]	➢ Deterministic ➢ Single-stage supply chain ➢ Single objective problem	➢ Stochastic ➢ Multi-stage supply chain ➢ Multi objective problem ➢ Considers transfer prices ➢ Economies of scale present in production ➢ Enables adjusting different service levels for each customer ➢ Considers different transportation modes with different lead-times
Schmidt and Wilhelm [39]	➢ Deterministic ➢ Single objective problem	➢ Stochastic ➢ Multi objective problem ➢ Considers varying exchange ➢ Considers tariff rates and transfer prices ➢ Economies of scale present in production ➢ Enables adjusting different service levels for each customer ➢ Considers different transportation modes with different lead-times
Syam [42]	➢ Deterministic	➢ Stochastic

	➢ Single-stage supply chain ➢ Single objective problem	➢ Multi-stage supply chain ➢ Multi objective problem ➢ Considers varying exchange and tariff rates ➢ Considers transfer prices ➢ Enables adjusting different service levels for each customer ➢ Considers different transportation modes with different lead-times
Goetschalckx et al. [14] and [45]	➢ Deterministic ➢ Single objective problem	➢ Stochastic ➢ Multi objective problem ➢ Considers varying exchange and tariff rates ➢ Economies of scale present in production ➢ Enables adjusting different service levels for each customer
Bhutta et al. [3]	➢ Deterministic ➢ Single-stage supply chain ➢ Single objective problem	➢ Stochastic ➢ Multi-stage supply chain ➢ Multi objective problem ➢ Considers transfer prices ➢ Economies of scale present in production ➢ Enables adjusting different service levels for each customer
Wilhelm et al [48]	➢ Deterministic ➢ Single objective problem	➢ Stochastic ➢ Multi objective problem ➢ Economies of scale present in production ➢ Enables adjusting different service

		levels for each customer
Robinson and Bookbinder [35]	➢ Deterministic ➢ Single objective problem	➢ Stochastic ➢ Multi objective problem ➢ Considers tariff rates and transfer prices ➢ Economies of scale present in production ➢ Considers capacity expansion decisions ➢ Enables adjusting different service levels for each customer

3. Design and methodology

3.1. Problem description

As previously mentioned an important issue that calls for attention is that in today's volatile marketplace the competitive advantage is not only gained through the appropriate manufacturing strategy, but is also achieved through an appropriate supply chain strategy. Lean production paradigm has positively impacted many markets where the winning criterion is cost; however, in many other fluctuating markets service level is the leading criterion for winning the market and that is when the agile supply chain paradigm needs to be considered.

As the result, the overall objectives of the problem are minimization of costs and maximization of the customer service level which is defined as the average of the expected sales over the expected demand for the entire planning horizon. As previously mentioned the focus should be on minimizing the *overall* costs, since moving directly to the locations with the lower costs is not always the best option and several other trades-offs should be considered in order to make the appropriate decisions. The global supply chain network consists of manufacturing facilities, distribution centers and customers at domestic and international locations, which is depicted in Figure 3. The model allows capacity expansion over the maximum available capacity up to some point at each facility. This feature of the model captures the trade-off between capacity expansion decisions, and moving production to the facilities with higher available capacity.

Stochastic customer demand can be met from any distribution center, via different transportation modes. Depending on the lost sale and overstocking costs and penalties, type and importance of the products or customers or any other policies or considerations the company might pursue, different target service levels or transportation modes with longer or shorter lead-times might be selected.

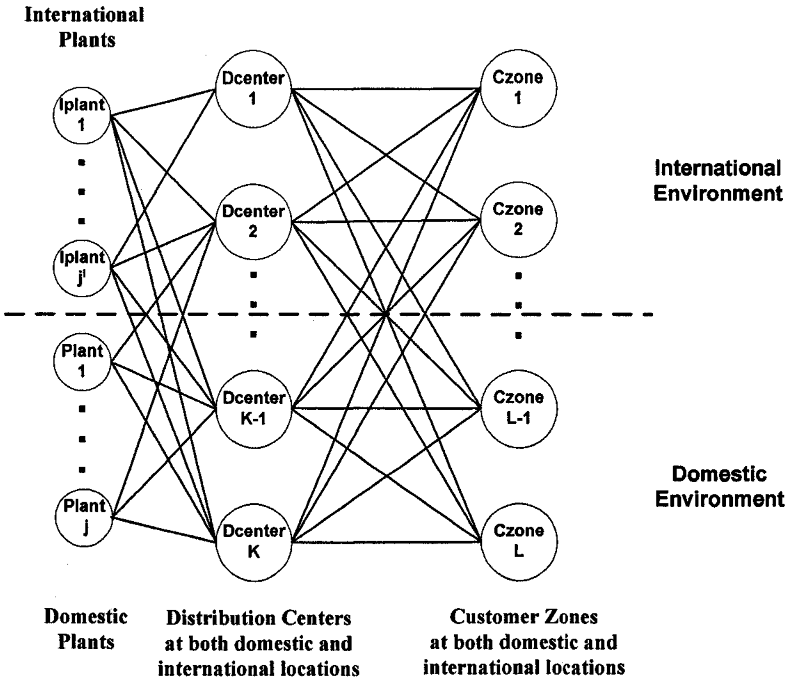

Figure 3 Global supply chain network configuration

3.2. Objective Function

A verbal description of the objective functions and constraints is given in this section followed by the corresponding mathematical formulations. The multiple objective functions are minimization of costs and maximization of the expected average service level:

Minimize Total Cost:

- Expected Overstock cost
- Expected lost sales cost
- Production costs
- Transportation cost s
- Capacity expansion costs
- Tariff costs
- Transfer costs
- Inventory costs

Maximize $$\text{Expected Service level} = \frac{\text{Expected sales}}{\text{Expected demand}}$$

3.3. Constraints

- Capacity constraints
  - Domestic manufacturing facilities capacity constraint
  - International manufacturing facilities capacity constraint
- Inventory and material balance constraints
  - Flow conservation at international manufacturing facilities
  - Flow conservation at domestic manufacturing facilities
  - Flow conservation at distribution centers
  - Sales and overstock constraint at customer zones

The solution of the multi-objective problem consists of a set of Pareto optimal global supply chain network configurations which is obtained by using the ε-constraint method [19]. Based on this method, the minimization of the total cost is kept as the objective function, and maximization of the expected service level is added as a constraint to the model, bounded by some feasible ε. Different levels of ε generate the entire Pareto optimal set [16] and we seek to find the maximum allowable ε until the decision maker is satisfied with the level of service.

3.4. Stochastic variables

As previously mentioned our model considers two possible cases to address the stochastic variables. The first case assumes that the demand, which is the stochastic variable in our case, follows a known probability distribution. Without loss of generality we assume that the stochastic variables follow the normal distribution with known mean and standard deviation for each period.

The other approach is most suitable for the situations where the probability distribution of the stochastic parameter is not known. In this case we implement the scenario-based approach. In this approach the decision maker makes some decisions in the first-stage, after which a random event occurs affected by the outcome of the first-stage decisions. The second-stage decisions compensate for any bad effects that might have been experienced as a result of the first-stage decisions [54].

In the proposed model in this thesis, production, outsourcing and capacity expansion decisions are first-stage decisions which are made prior to the demand realization, while the expected sales which result in expected lost sale and overstocking costs are second- stage variables which are postponed until the uncertain parameter is realized, which result in the fulfillment of the demand with respect to the target service level.

3.5. Model notation

The model is a stochastic mixed-integer nonlinear optimization problem with the following components presented in Table 2.

Table 2 Model notation

Notation	
Sets and indices	
j	Domestic manufacturing facilities
j^I	International manufacturing facilities
k	Distribution centers
l	Customer zones
p	Production quantity range for domestic plant j
q	Production quantity range for international plant j^I
s	Individual realization scenarios of the stochastic variable (low, medium, high)
js	Joint probabilities of realization scenarios
r	Transportation modes
t	Time periods

m	Transportation quantity interval
Decision variables	
x	The random stochastic variable representing the stochastic demand
Qj_{jt}	Quantity of products produced at domestic plant j in period t
$QjI_{j^I t}$	Quantity of products produced at international plant j^I in period t
Qjk_{jkrt}	Quantity of products shipped from domestic plant j to distribution center k via mode r in period t
$QjIk_{j^I krt}$	Quantity of products shipped from international plant j^I to distribution center k via mode r in period t
Qkl_{klrt}	Quantity of products shipped from distribution center k to customer zone l via mode r in period t
Ij_{jt}	Ending inventory level at domestic plant j in period t
$IjI_{j^I t}$	Ending inventory level at international plant j^I in period t
Ik_{kt}	Ending inventory level at distribution center k in period t
$LostSale_{lt}$	Lost sale amount at customer zone l in period t
$OverStock_{lt}$	Over stocked amount at customer zone l in period t
$Sales^{s}_{lt,js}$	Stochastic sales to customer zone l in period t under joint scenario js
$Lostsale^{s}_{lt,js}$	Stochastic lost sale of customer zone l demand in period t under joint realization scenario js
$Overstock^{s}_{lt,js}$	Stochastic overstock of the customer zone l demand in period t under joint realization scenario js
$Capj_{jt}$	Capacity level at domestic plant j in period t
$CapjI_{j^I t}$	Capacity level at international plant j^I in period t
u_{jkrtm}	Binary variable representing the interval to which the shipment quantity form j to k belongs
$w_{j^I krtm}$	Binary variable representing the interval to which the shipment quantity form j^I to k belongs
y_{klrtm}	Binary variable representing the interval to which the shipment quantity form k to l belongs
Other notation	
$TCapCj$	Total capacity expansion cost at domestic plants
$TCapCjI$	Total capacity expansion cost at international plants
$\Pr Cj_{jt}$	Production cost at domestic plants j in period t
$\Pr CjI_{j^I t}$	Production cost at international plants j^I in period t
$T\Pr Cj$	Total production cost at domestic plants
$T\Pr CjI$	Total production cost at international plants
$TTrCj$	Total transportation cost from domestic plants to distribution centers
$TTrCjI$	Total transportation cost from international plants to distribution centers
$TTrCk$	Total transportation cost from distribution centers to customer zones
$TCapCj$	Total capacity expansion cost at domestic plants
$TCapCjI$	Total capacity expansion cost at international plants
$TICj$	Total inventory cost at domestic plants
$TICjI$	Total inventory cost at international plants

$TICk$	Total inventory cost at distribution centers
$TTariffC$	Total tariff cost
$TTrprice$	Total transfer cost
$TLostC$	Total lost sale cost
$TOverC$	Total overstock cost
$TCost$	Total cost to be minimized
ASL	Stochastic average service level to be maximized
Parameters	
$f(x)$	The general probability density function of the stochastic variable
μ	Mean demand
σ	Standard deviation of the demand
$demand_{l,js}^{s}$	Possible outcome of the stochastic demand at customer zone l under joint scenario js
ξ_{js}	Joint probability of the possible outcome of the demand at customer zone l under joint scenario js
$Capj\max_{j}$	Maximum available capacity at domestic plant j
$Capj\,Im\,ax_{j^{I}}$	Maximum available capacity at international plant j^{I}
$CapCj_{j}$	Unit capacity expansion cost at domestic plant j
$CapCjI_{j^{I}}$	Unit capacity expansion cost at international plant j^{I}
$UpperDomesticCap_{j}$	Maximum allowable capacity at the domestic plant j
$UpperInternationalCap_{j^{I}}$	Maximum allowable capacity at the international plant j^{I}
$\overline{Qp_{p}}$	Upper bound for range p of production flow at domestic plant j
$\overline{Qq_{q}}$	Upper bound for range q of production flow at international plant j^{I}
$\overline{UPCp_{p}}$	Production cost which corresponds to interval p for domestic plant j
$\overline{UPCq_{q}}$	Production cost which corresponds to interval q for international plant j^{I}
$U\Pr Cj_{j}$	Unit production cost at domestic plant j (disregarding economies of scale)
$U\Pr CjI_{j^{I}}$	Unit production cost at international plant j^{I} (disregarding economies of scale)
$UICj_{j}$	Unit inventory cost at domestic plant j
$UICjI_{j^{I}}$	Unit inventory cost at international plant j^{I}
$UICk_{k}$	Unit inventory cost at distribution center k
PI	Pipeline inventory cost per period per unit of product
$UTCj_{jkr}$	Unit transportation cost from domestic plant j to distribution center k via r
$UTCjI_{j^{I}kr}$	Unit transportation cost from international plant j^{I} to distribution center k via r
$UTCk_{klr}$	Unit transportation cost from distribution center k to customer l via r
b_{jrm}	Unit transportation cost reduction percentage for shipment from j via r, corresponding to interval m

$d_{j^I rm}$	Unit transportation cost reduction percentage for shipment from j^I via r, corresponding to interval m
e_{krm}	Unit transportation cost reduction percentage for shipment from k via r, corresponding to interval m
$jLower_{jrm}$	Lower bound on shipment quantity from j via r, corresponding to interval m
$jILower_{j^I rm}$	Lower bound on shipment quantity from j^I via r, corresponding to interval m
$kLower_{krm}$	Lower bound on shipment quantity from k via r, corresponding to interval m
$jUpper_{jrm}$	Upper bound on shipment quantity from j via r, corresponding to interval m
$jIUpper_{j^I rm}$	Upper bound on shipment quantity from j^I via r, corresponding to interval m
$kUpper_{krm}$	Upper bound on shipment quantity from k via r, corresponding to interval m
LTj_{jkr}	Lead-time of transportation from domestic plant j to distribution center k via r
$LTjI_{j^I kr}$	Lead-time of transportation from international plant j^I to distribution center k via r
LTj_{klr}	Lead-time of transportation from distribution center k to customer zone l via r
LC	Unit lost sale penalty
OC	Unit overstocking penalty
$TariffInternational_{j^I k}$	Tariff rate from international plant j^I to distribution center k
$TariffDomestic_{jk}$	Tariff rate from domestic plant j to distribution center k
TP_{jk}	Transfer price of plant j to distribution enter k
$E_{j^I t}$	Exchange rate of currency of the international plant j^I
ε	Minimum required customer expected average service level
J	Total number of domestic manufacturing facilities
J^I	Total number of international manufacturing facilities
L	Total number of customers
T	Total number of planning periods

3.6. Two-stage stochastic programming (distribution-based approach)

In this section we explain the stochastic model in which the stochastic variable follows a known probability distribution. Our aim is to minimize the cost over the first-stage variables and the expected cost of the second-stage variables with respect to the minimum required service level.

3.6.1. Objective function

3.6.1.1. Expected lost sale and overstock cost

As previously mentioned the amount shipped to the customers is a second-stage variable and should be tackled after the realization of the stochastic variable. This leads to expected lost sale or overstock costs. The standard news boy formulation is adapted here to calculate the expected overstock cost:

$$TOverC = \sum_{l}\sum_{t}\int_{0}^{\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}}} OC(\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} - x) f(x)dx \qquad (1)$$

The demand is modeled as normally distributed. This approach is frequently used in the literature and captures the essential features of demand uncertainty. There are two possible situations for the overstocked items: in the first one the overstocked items are sold at lower prices in the following periods or perished after the current planning period, and *OC* is the unit overstocking penalty which represents the loss resulted from the lower selling price, or the disposal cost of the overstocked item. The calculation for the first possibility is given in formula (1a). The second possibility is that the overstocked items do not perish, or can be sold at the same prices in the following periods; as a result they can be kept at the customer zones and be sold in the upcoming periods and *OC* will represent the holding costs for the overstocked items. In this case we have to make a change in the overstock cost calculation, resulting in formula (1b).

$$OverStock_{lt} = \int_{0}^{\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}}} (\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} - x) f(x)dx \quad \forall l,t \qquad (1a)$$

$$OverStock_{lt} = \int_{0}^{\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} + Overstock_{l,t-1}} (\sum_{k}\sum_{r} (Qkl_{klr,t-LTk_{klr}} + Overstock_{l,t-1}) - x) f(x)dx \quad \forall l,t \qquad (1b)$$

Assuming the normal distribution function for the stochastic variables, we calculate the expected overstock cost:

$$\sum_{l}\sum_{t}\int_{0}^{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}} OC(\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} - x)f(x)dx$$

$$= OC \times \sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} \int_{0}^{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}} f(x)dx - OC \int_{0}^{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}} xf(x)dx$$

$$= OC \times \sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} \left(\frac{1}{2} erf(\frac{z}{\sqrt{2}})\right]_{\frac{-\mu}{\sigma}}^{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}} - \mu}{\sigma}}$$

$$- OC(-\frac{\sigma}{\sqrt{2\pi}} \times e^{\frac{-Z^2}{2}}\Bigg]_{\frac{-\mu}{\sigma}}^{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}} - \mu}{\sigma}} + \left(\frac{\mu}{2} erf(\frac{z}{\sqrt{2}})\right]_{\frac{-\mu}{\sigma}}^{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}} - \mu}{\sigma}}$$

Where: $erf(z) = \frac{2}{\sqrt{\pi}} \int_{0}^{z} e^{-t^2} dt$ and $z = \frac{x-\mu}{\sigma}$ (2)

The lost sale cost assuming that the stochastic variables follow the normal distribution, is of the following form:

$$TLostC = \sum_{l}\sum_{t} \int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} LC(x - \sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}})f(x)dx \qquad (3)$$

As we previously mentioned if the overstocked items are to be disposed, we use the calculation in (3a) to calculate the lost sale amount for each customer zone in each planning period, otherwise the overstocked items in the previous periods are used to satisfy the demand at the current period, resulting in the calculation mentioned in (3b).

$$LostSale_{lt} = \int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} (x - \sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}})f(x)dx \qquad \forall l,t \qquad (3a)$$

$$LostSale_{lt} = \int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}} + OverStock_{l,t-1}}^{\infty} (x - \sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}} - OverStock_{l,t-1})f(x)dx$$

$$\forall l,t \qquad (3b)$$

Applying the same procedure, we calculate the lost sale cost:

$$\sum_{l}\sum_{t}\int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} LC(x-\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}})f(x)dx$$

$$=-LC\times\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}}\int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} f(x)d_x+LC\int_{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} xf(x)dx$$

$$=-LC\times\sum_{k}\sum_{r} Qkl_{klr,t-LTk_{klr}}\left(\frac{1}{2}erf(\frac{z}{\sqrt{2}})\right]^{\infty}_{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}}$$

$$+LC(-\frac{\sigma}{\sqrt{2\pi}}\times e^{\frac{-Z^2}{2}}\Bigg]^{\infty}_{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}}+\left(\frac{\mu}{2}erf(\frac{z}{\sqrt{2}})\right]^{\infty}_{\frac{\sum_k\sum_r Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}})$$

3.6.1.2. Production cost

Economies of scale are present in production costs. The production amount is divided into NR sub-ranges, each corresponding to lower unit production costs, and the total production cost is modeled as a piecewise linear function of the production amount as shown in Figure 4.

In order to calculate the total production costs at domestic plants we introduce the binary variable Vp_{jpt}, which defines the range the production amount belongs to:

$$Vp_{jpt}=\begin{cases}1, \text{ if } Q\in\left[\overline{Q}p_{p-1},\overline{Q}p_{p}\right]\\ 0, \text{ otherwise;}\end{cases} \tag{4}$$

In order to ensure that the production amount belongs to only one sub-range, we use the following constraints:

$$\sum_{p=1}^{NR_j} Vp_{jpt}=1 \qquad\qquad \forall j,t \tag{5}$$

The production amount is then modeled as:

$$\overline{Q}p_{p-1}Vp_{jpt} \le Qp_{jpt} \le \overline{Q}p_{p}Vp_{jpt} \qquad \forall j,t,p=1,\dots,NR_j \tag{6}$$

$$Qj_{jt} = \sum_{p=1}^{NR_j} Qp_{jpt} \qquad \forall j,t \tag{7}$$

Finally the total production cost at the domestic plants is calculated as:

$$T\Pr Cj = \sum_{j}\sum_{t}\sum_{p=1}^{NR_j}\left[\overline{UPCp}_{p-1}Vp_{jpt} + (Qp_{jpt} - \overline{Q}p_{p-1}Vp_{jpt})\frac{\overline{UPCp}_{p} - \overline{UPCp}_{p-1}}{\overline{Q}p_{p} - \overline{Q}p_{p-1}}\right] \tag{8}$$

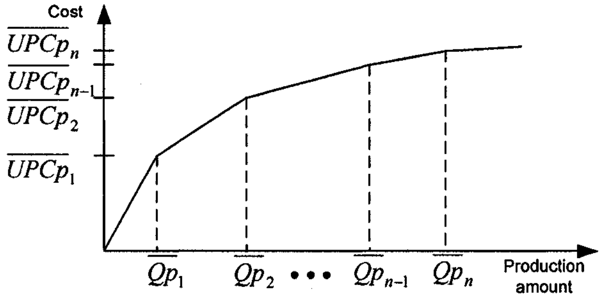

Figure 4 Economies of scale in production cost

We take the same procedure to calculate the total production costs at international plants. The total production cost consists of the total production costs at domestic plants, and the total production costs at international plants considering the exchange rate factor. The Total production cost is calculated as: $T\Pr Cj + \frac{1}{E_{j't}} \times T\Pr CjI$ (9)

3.6.1.3. Transportation cost

The transportation cost incurred at the plants and distribution centers is assumed to be proportional to the amount of shipment with a constant unit transportation cost as well as the pipeline inventory cost [35]. The corresponding term in the objective function is of the following form:

$$TTrCj = \sum_{j}\sum_{k}\sum_{r}\sum_{t}(UTCj_{jkr} + PI \times LTj_{jkr})Qjk_{jkrt} \tag{10}$$

$$TTrCjI = \sum_{j'}\sum_{k}\sum_{r}\sum_{t}\frac{1}{E_{j't}}(UTCjI_{j'kr} + PI \times LTjI_{j'kr})QjIk_{j'krt} \tag{11}$$

$$TTrCk = \sum_{k}\sum_{l}\sum_{r}\sum_{t}(UTCk_{klr} + PI \times LTk_{klr})Qkl_{klrt} \tag{12}$$

3.6.1.3.1. Economies of scale in transportation costs

If we consider economies of scale in transportation costs, the previously mentioned calculations should be modified in trems of unit transportation costs from each manufacturing or distribution facility via each transportation mode. Depending on the shipment quantities between different manufacturing and distribution facilities, and also the type of the transportation mode, different economies of scale or cost reduction factors are considered which affect the unit transportation costs. Considering the economies of scale, the modified transportation costs are calculated as followed:

$$TTrCj = \sum_{j}\sum_{k}\sum_{r}\sum_{t}(UTCj_{jkr} \times \sum_{m}(1-b_{jrm})u_{jkrtm} + PI \times LTj_{jkr})Qjk_{jkrt} \tag{10a}$$

$$TTrCjI = \sum_{j'}\sum_{k}\sum_{r}\sum_{t}\frac{1}{E_{j't}}(UTCjI_{j'kr} \times \sum_{m}(1-d_{j'rm})w_{j'krtm} + PI \times LTjI_{j'kr})QjIk_{j'krt} \tag{11a}$$

$$TTrCk = \sum_{k}\sum_{l}\sum_{r}\sum_{t}(UTCk_{klr} \times \sum_{m}(1-e_{krm})y_{klrtm} + PI \times LTk_{klr})Qkl_{klrt} \tag{12a}$$

The binary variables u_{jkrtm}, $w_{j'krtm}$ and y_{klrtm} are defined in constraints (27)-(29), and determine the interval to which the shipment amount between the manufacturing facilities to the distribution facilities, or from the distribution facilities to the customer zones belong, and the parameters b_{jrm}, $d_{j'rm}$ and e_{krm} represent the percentage of cost reduction in unit transportation costs, from each manufacturing or distribution facility , using transportation mode *r* which corresponds to the quantity interval *m*.

3.6.1.4. Capacity expansion cost

The model allows the expansion of capacity over the maximum amount of available resources. Here the model decides between outsourcing the production to the international plants with greater capacity, and expanding the existing capacity at the domestic plants. It is assumed that the capacity expansion cost is lower at international locations.

$$TCapCj = \sum_{j}\sum_{t} CapCj_{j} \times \max(0, Capj_{jt} - Capj\max_{j}) \tag{13}$$

$$TCapCjI = \sum_{j'}\sum_{t} \frac{1}{E_{j't}} \times CapCjI_{j'} \times \max(0, CapjI_{j't} - Capj\mathrm{Im}\,ax_{j'}) \tag{14}$$

3.6.1.5. Inventory cost

Inventory cost at the manufacturing and distribution facilities are assumed to be proportional to the amount kept in inventory with respect to the unit inventory cost.

$$TICj = \sum_{j}\sum_{t} UICj_{j} \times Ij_{jt} \tag{15}$$

$$TICjI = \sum_{j'}\sum_{t} \frac{1}{E_{j't}} \times UICjI_{j'} \times IjI_{j't} \tag{16}$$

$$TICk = \sum_{k}\sum_{t} UICk_{k} \times Ik_{kt} \tag{17}$$

3.6.1.6. Tariff cost

Countries impose various restrictions on products coming into their markets, sometimes in shape of tariff or import duties, which is usually expressed as a percentage of the selling price or the manufacturing cost [3]. In our model it happens whenever the production is outsourced to the international manufacturing facilities and is then shipped to the distribution centers in other countries. The tariff cost is expressed as a percentage of the total manufacturing costs incurred at the international plants.This percentage which expresses the tariff rates, varies between each two different countries.

$$TTariffC = \sum_{j'} \sum_{t} \frac{1}{E_{j't}} \times TariffInternational_{j'k} \times T\,\mathrm{Pr}\,CjI \qquad (18)$$

3.6.1.7. Transfer cost

Transfer cost is incurred whenever products are shipped between two facilities of the same company and is calculated with respect to the transfer prices and tariff rates [14], [45] and [48].

$$TTrprice = \sum_{j} \sum_{k} TP_{jk} \times (1 + TariffDomestic_{jk}) \times (\sum_{r} \sum_{t} Qjk_{jkrt}) \qquad (19)$$

The objective function of minimizing the overall costs is developed by the summation of all costs: (1 and 3), (9-19).

3.6.2. Constraints

In this section we explain the problem constraints. The capacity of the manufacturing facilities at both domestic and international locations should be at least equal to the production amount at the facilities. This allows the production amount exceed the maximum available capacity at each facility at the expense of incurring capacity expansion costs. Of course the capacity expansion can not be done more than some certain amount which is defined by the decision maker, and after that level the production should be done at other manufacturing facilities in either undercapacity or overcapacity mode.

$$Qj_{jt} \le Capj_{jt} \le UpperDomesticCap_{j} \qquad \forall j,t \qquad (20)$$

$$QjI_{j't} \le CapjI_{j't} \le UpperInternationaCap_{j'} \qquad \forall j^{I},t \qquad (21)$$

The production level at each manufacturing plant in each period plus the remaining inventory level from the previous period must be equal to the total amount shipped from each plant to all distribution the centers by all transportation modes plus the excess inventory carried over to the following periods:

$$Qj_{jt} + Ij_{j,t-1} = \sum_{k}\sum_{r} Qjk_{jkrt} + Ij_{jt} \qquad \forall j,t \qquad (22)$$

$$QjI_{j^I t} + IjI_{j^I,t-1} = \sum_{k}\sum_{r} QjIk_{j^I krt} + IjI_{j^I t} \qquad \forall j^I,t \qquad (23)$$

If the initial inventory levels at the manufacturing facilities are assumed to be zero, the customer demand might be lost for the initial planning periods, depending on the lead-times between different stages of the supply chain. Of course if the decision maker assumes initial inventories at the manufacturing facilities, the service level improves and the value of $Ij_{j,0}$ and $IjI_{j^I,0}$ would be a positivevalue.

$$Ij_{j,0} = IjI_{j^I 0} = 0 \qquad \forall j, j^I \qquad (24)$$

The total amount each distribution center ships to the customer zones via all transportation modes plus the excess inventory carried over to the following periods, should be equal the sum of the amounts received from all the domestic and international facilities by all transportation modes considering the respecting lead-times, plus the remaining inventory from the previous period. If the decision maker assigns initial inventory levels at the distribution centers, the service level can be further improved and the value of $Ik_{k,0}$ would be non-zero.

$$\sum_{j}\sum_{r} Qjk_{jkr,t-LTj_{jk}} + \sum_{j^I}\sum_{r} QjIk_{j^I kr,t-LTj_{jIk}} + Ik_{k,t-1} = \sum_{l}\sum_{r} Qkl_{klrt} + Ik_{kt}$$

$$\forall k,t \qquad (25)$$

$$Ik_{k,0} = 0 \qquad \forall k,t \qquad (26)$$

If we assume economies of scale in unit transportation costs, in order to define the binary variables which determine the interval to which shipment amounts belong, we need to add the following constraints to the previously mentioned problem constraints:

$$jLower_{jrm} \times u_{jkrtm} \le Qjk_{jkrt} \le jUpper_{jrm} \times u_{jkrtm} \qquad (27)$$

$$jILower_{j'rm} \times w_{j'krtm} \le QjIk_{j'krt} \le jIUpper_{j'rm} \times w_{j'krtm} \tag{28}$$

$$kLower_{krm} \times y_{klrtm} \le Qkl_{klrt} \le kUpper_{krm} \times y_{klrtm} \tag{29}$$

The above mentioned constraints consider the lower bounds and upper bounds of the intervals, and define the range to which the transportation quantities belong, in order to obtain the cost reduction percentage that corresponds to that interval.

Using the ε - constraint method, the objective of maximizing the expected average service level has been added to the problem constraints, bounded by the minimum accepted service level ε. The demand is uncertain and in order to define the production and transportation levels, the expected average service level is used as a measure, which gives the decision maker the tool for imposing the company policies in terms of the extent of meeting the demand for each specific customer

The expected service level is defined as the expected sales over the expected demand [16] and [11]. The expected demand is known for each customer, and the expected sales is calculated in both circumstances that the total production is either more or less than the realized demand, which might lead to expected overstocking or lost sales respectively. The expected average service level is calculated as follows:

$$\frac{1}{L \times T} \sum_{l} \sum_{t} \frac{\int_{0}^{\sum_k \sum_r Qkl_{klr,t-LTk_{klr}}} x f(x) dx + \int_{\sum_k \sum_r Qkl_{klr,t-LTk_{klr}}}^{\infty} \sum_{k} \sum_{r} Qkl_{klr,t-LTk_{klr}} f(x) dx}{\int_{0}^{\infty} x f(x) dx} \ge \varepsilon \tag{30}$$

As previously mentioned, if we assume that the overstocked items do not perish and can be used to satisfy the demand in the following periods, we have to use the calculations in (30a).

$$\frac{1}{L \times T}\sum_{l}\sum_{t}\frac{\int_{0}^{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}+OverStock_{l,t-1}} xf(x)dx + \int_{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}+OverStock_{l,t-1}}^{\infty}(\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}} + OverStock_{l,t-1})f(x)dx}{\int_{0}^{\infty} xf(x)dx} \geq \varepsilon$$

(30a)

The initial overstock amount is assumed to be zero: $OverStock_{l,t-1} = 0$ (30b)

Assuming the normal probability distribution for the uncertain customer demand results in the following calculations:

$$\int_{0}^{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}} xf(x)dx + \int_{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}}^{\infty}\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}f(x)dx$$

$$= -\frac{\sigma}{\sqrt{2\pi}}\times e^{\frac{-Z^2}{2}}\Bigg]_{\frac{-\mu}{\sigma}}^{\frac{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}} + \left(\frac{\mu}{2}erf(\frac{z}{\sqrt{2}})\right]_{\frac{-\mu}{\sigma}}^{\frac{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}}$$

$$+\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}\left(\frac{1}{2}erf(\frac{z}{\sqrt{2}})\right]_{\frac{\sum_{k}\sum_{r}Qkl_{klr,t-LTk_{klr}}-\mu}{\sigma}}^{\infty}$$

Finally all we present the non-negativity and binary constraints:

$Vp_{pjt}, Vq_{qj't}, u_{jkrtm}, w_{j'krtm}, y_{klrtm} \in \{0,1\}$ (31)

all variables ≥ 0 (32)

3.7. Two-stage stochastic programming (scenario-based approach)

Here we assume that there is not enough available information about the probability distributions of the stochastic variables, but based on historical data several scenarios with known probabilities can be generated which help model the uncertainties in the problem (Scenario-based approach).

3.7.1. Objective function

In this approach the uncertainty is represented in terms of several discrete realization scenarios of the stochastic variables. The previously mentioned formulation needs to be modified to represent the multiple scenarios which are used to capture the uncertainties. The objective is to find the best solution under all scenarios, which minimizes the total cost of the first-stage variables plus the expected cost of the second-stage variables, regarding the minimum target service level.

The only terms that should be modified in the previously mentioned objective function are the expected overstocking and lost sale costs which are calculated based on the second-stage variables, and the associated costs are calculated with respect to the penalties under each joint scenario. This gives the decision maker the flexibility to adjust the service level and the probability of meeting the demand for each customer zone individually.

$$\sum_{js=1}^{NS} \xi_{js} \sum_{l} \sum_{t} \left[LC \times LostSale_{lt,js}^{s} + OC \times Overstock_{lt,js}^{s} \right] \tag{33}$$

The overall objective of the problem with discrete stochastic parameters is modeled by using equations (9)-(19) and (33).

3.7.2. Constraints

We consider three demand realizations scenarios: high, medium and low, to capture optimistic, likely and pessimistic possible outcomes of the demand for each customer [43]. This leads to $N_{js} = 3^{L}$ joint demand scenarios with their corresponding probabilities, where L is the total number of customer zones. We assume the probability of the occurrence of each scenario s for each customer zone is known, and thus the probability of occurrence of the joint scenarios js, can also be calculated. The joint probabilities will satisfy: $\sum_{js=1}^{Njs} \xi_{js} = 1$

It should be noted that the decision variables with superscript s correspond to the second-stage stochastic decision variables. We adopt the previously mentioned constraints (20)-(29) and (31)-(32) and introduce the new constraints for the discrete case.

The decisions on expected sales, expected overstock and expected lost sale, which are second-stage variables, are postponed until the realization of the stochastic variable; thus the amount shipped from the distribution centers to the each customer zone via all transportation modes, results in sales or overstocking regarding the target service level under each joint scenario.

$$\sum_k \sum_r Q_{kl,t-LTk_{klr}} = Sales^s_{lt,js} + Overstock^s_{lt,js} \qquad \forall l,t,js \qquad (34)$$

If we assume that the overstocked items do not perish and can be used to satisfy the demand in the following periods, we use the constraint (34a)

$$\sum_k \sum_r Q_{kl,t-LTk_{klr}} + Overstock^s_{l,t-1,js} = Sales^s_{lt,js} + Overstock^s_{lt,js} \qquad \forall l,t,js \qquad (34a)$$

The initial overstock amount is assumed to be zero at each customer zone, under each joint scenario:

$$OverStock^s_{l,0,js} = 0 \qquad \forall l,js \qquad (34b)$$

The stochastic lost sale for each customer and time period is the difference between the stochastic demand and the stochastic sales under each joint scenario.

$$Lostsale^s_{l,t,js} = demand^s_{l,js} - Sales^s_{lt,js} \qquad \forall l,t,js \qquad (35)$$

The stochastic sales to each customer can not exceed the total amount shipped to the customers, or each customer demand. If the realized demand is smaller than the shipped amount, the stochastic sales can not exceed the demand, and if the realized demand is greater than the shipped amount, the stochastic sales can not exceed the amount shipped, under each scenario and time period.

$$Sales^{s}_{lt,js} \leq \min(demand^{s}_{l,js}, \sum_{k}\sum_{r} Q_{kl,t-LTk_{klr}}) \qquad \forall l,t,js \qquad (36)$$

Again assuming that the overstocked items in the previous periods can be used to fulfill the demand in the current period, we adapt the constraints (36a).

$$Sales^{s}_{lt,js} \leq \min(demand^{s}_{l,js}, \sum_{k}\sum_{r} Q_{kl,t-LTk_{klr}} + OverStock_{l,t-1,js}) \qquad \forall l,t,js \qquad (36a)$$

Using the ε - constraint method, the objective of maximizing the expected average service level has been added to the problem constraints, bounded by the minimum accepted service level ε. The expected average service level is defined as the expected sales over the expected demand. The expected demand is calculated for each customer, and the expected sale is calculated as follows:

$$ASL = \frac{1}{L \times T} \sum_{l}\sum_{t} \frac{\sum_{js} \xi_{js} \times Sales^{s}_{lt,js}}{\sum_{js} \xi_{js} \times demand^{s}_{l,js}} \geq \varepsilon \qquad (37)$$

4. Results and Analysis

4.1. Overview

In this section we analyze a special case of our model to obtain useful and practical managerial insights into the nature of the first-stage decisions including the capacity expansion, outsourcing and facility selection decisions in a global environment and to propose a heuristic solution procedure to decide on first-stage decisions for large- scale problem that the commercial software might not be able to solve with reasonable computational efforts.

The analytical model holds almost all the features of the proposed model; however, we have made some assumptions in order to simplify the model and make it more manageable for analysis. The simplification we have made is assuming centralized distribution [24], meaning a single distribution center with identical transportation modes and lead-times which acts as a hub between the manufacturing facilities and customer zones.

An alternative assumption to replace the centralized distribution is assuming identical distribution centers in terms of the distance or transportation costs to the customer zones; since they are parts of the second-stage decisions and out of the scope of the proposed heuristic method, of course the distance to the manufacturing facilities can vary as it is part of the first-stage decisions.

As previously mentioned, in the two-stage programming method the first-stage decisions are made prior to the realization of the stochastic variables and the second-stage decisions are the affected by the first-stage decisions [54]. In our model the amount each manufacturing facility should produce, the extent each facility should expand its capacity or outsource to the international plants, are first-stage decision variables. The minimum acceptable expected service level is also a first-stage variable as the decision maker should decide on it prior to the demand realization. Of course the real service level can not be known unless the real demand is observed; as a result even the expected service level already set to 100% might lead to lost sales or overstocks.

We finally propose a heuristic method to determine the first-stage decision variables of the simplified model and then compare the results with the ones obtained by the GAMS commercial software. The classification of the first-stage and second-stage decisions in the proposed model is given in Table 3.

Table 3 First-stage and second-stage decisions

First-stage decision variables	**Second-stage decision variables**
Production amount at the manufacturing facilities	Shipment amount to the customers
Shipment amount from manufacturing facilities to the distribution center	
Capacity expansion decisions	Transportation costs to the customers
Outsourcing decisions	
Production costs	Expected lost sale costs
Transportation costs to the distribution center	
Capacity expansion costs	Expected overstock costs
Transfer costs	
Tariff costs	Inventory costs
Minimum accepted expected average service level	

4.2. Analytical model and managerial insights

In this section we intend to present useful and practical managerial insights on some of the most important first-stage decision variables of our model: production, outsourcing and capacity expansion decisions. The analytical case addresses a multi-stage, multi-period, multi-facility model, assuming centralized distribution with identical transportation modes. In order to solve the analytical model, we form the Lagrangian relaxation of the problem tackling the first stage decision variables and their respecting constraints, and to calculate the increase in the objective function based on each decision variable, we need to calculate the derivative of the relaxed problem based on each variable. Of course we can perform this operation on continuous decision variables. The unit production cost considering economies of scale was modeled as a piece-wise linear function, which is discrete and could not be handled that way in the analytical model, as the result we need to disregard the economies of scale in production in the analytical model.

In order to calculate the sensitivity of the objective function to the first-stage decision variables which are the production amount at each of the manufacturing facilities, and the shipment amount from the manufacturing facilities to the distribution centers, we decompose the problem into two parts, one addressing the first-stage decisions and the other one tackling second-stage decisions. In the relaxed version of the model all the transportation modes and lead-times are identical and thus the index r which represents the transportation modes has been removed from all the decision variables.

In order to form the relaxed problem we just consider the terms and constraints that are related to the first-stage variables; as a result we only relax constraints (22) and (23) which address the production decision variables and the shipment amount to the centralized distribution center. The rest of the constraints both in discrete and continuous case are at the distribution center or customer zone level, which tackle the second-stage variables, and thus not considered in the analysis of first-stage variables in analytical model. The relaxed form of the simplified problem considering either a single centralized distribution center or identical distribution centers is of the following form:

$$\operatorname{Re} laxedObj =$$

$$\sum_j \sum_t U \Pr Cj_j \times Qj_{jt} + \sum_{j'} \sum_t \frac{1}{E_{'It}} \times U \Pr CjI_{j'} \times QjI_{j't}$$

$$+ \sum \sum \sum UTCj_{jk} \times Qjk_{jkt}$$

$$+ \sum_{j'} \sum_k \sum_t \frac{1}{E_{j't}} (UTCjI_{j'k} \times QjIk_{j'kt})$$

$$+ \sum_{j'} \sum_k \sum_t \frac{1}{E_{j't}} (UTCjI_{j'k} \times QjIk_{j'kt})$$

$$+ \sum_k \sum_l \sum_t UTCk_{kl} \times Qkl_{klt}$$

$$+ \sum_j \sum_k TP_{jk} \times (1 + TariffDomestic_{jk})(\sum_t Qjk_{jkt})$$

$$+ \sum_{j'} \sum_t \frac{1}{E_{j't}} \times TariffInternational_{j'k} \times U \Pr CjI_{j'} \times QjI_{j't}$$

$$+ \sum_j \sum_t \alpha_{jt} \times (Qj_{jt} + Ij_{j,t-1} - \sum_k Qjk_{jkt} - Ij_{jt})$$

$$+ \sum_{j'} \sum_t \beta_{j't} \times (QjI_{j't} + IjI_{j,'t-1} - \sum_k QjIk_{j'kt} - IjI_{j't}) \qquad (38)$$

In the relaxed problem the coefficients α_{jt} and $\beta_{j't}$ correspond to the Lagrangian multipliers that are used to relax the constraints (22) and (23). It should be noted that the capacity expansion costs are not included in the relaxed problem as we are going to decide on the capacity expansion decisions and the respective costs analytically. In order to calculate the increase in the objective function for the relaxed problem, we take the derivative of the relaxed problem with respect to the production amounts at the domestic and international manufacturing facilities, and the shipment quantity to the centralized distribution center, or identical distribution centers:

$$\frac{\partial RObj}{\partial Qj_{jt}} = U \Pr Cj_j + \sum_j \sum_t \alpha_{jt} \qquad \forall j,t \qquad (38a)$$

$$\frac{\partial RObj}{\partial QjI_{j't}} = \frac{1}{E_{j't}} (U \Pr CjI_{j'})(1 + TariffInternational_{j'k}) + \sum_{j'} \sum_t \beta_{j't} \qquad \forall j^I, k, t \qquad (38b)$$

$$\frac{\partial RObj}{\partial Qjk_{jkt}} = UTCj_{jk} + TP(1 + TariffDomestic_{jk}) - \sum_j \sum_t \alpha_{jt} \qquad \forall j,k,t \qquad (38c)$$

$$\frac{\partial RObj}{\partial QjIk_{j'kt}} = \frac{1}{E_{j't}}(UTCjI_{j'k}) - \sum_{j'}\sum_{t}\beta_{j't} \qquad \forall j^{I},k,t \quad (38d)$$

Definition 1: The total sensitivity or increase in the objective function for the relaxed problem respecting the amount the domestic and international manufacturing facilities produce and ship to the centralized distribution center without considering the capacity expansion costs are:

$$\psi_{jk} = U\Pr Cj_{j} + UTCj_{jk} + TP(1 + TariffDomestic_{jk}) \qquad \forall j,k \quad (39)$$

$$\varpi_{j'kt} = \frac{1}{E_{j't}}(U\Pr CjI_{j'})(1 + TariffInternational_{j'}) + \frac{1}{E_{j't}}(UTCjI_{j'k}) \quad \forall j',k,t \, (40)$$

Definition 2: In order to include the capacity expansion decisions in the analytical model, we have to mention that capacity expansion does not happen unless there does not exist any other manufacturing facility that can operate within its available range of resources at a lower price. To model the capacity expansion costs in our analytical model we introduce two other parameters which represent the increase in the relaxed objective function with respect to the amount the domestic and international manufacturing facilities produce and ship to the centralized distribution center including the capacity expansion costs:

$$\lambda_{jk} = \psi_{jk} + CapCj_{j}\frac{\max(0, Capj_{jt} - Capj\max_{j})}{(Capj_{jt} - Capj\max_{j})} \qquad \forall j,k \quad (41)$$

$$\mu_{j'kt} = \varpi_{j'kt} + \frac{CapCj_{j}}{E_{j't}} \times \frac{\max(0, CapjI_{j't} - Capj\,\mathrm{Im}ax_{j'})}{(CapjI_{j't} - Capj\,\mathrm{Im}ax_{j'})} \qquad \forall j^{I},k,t \quad (42)$$

The term added to the previous coefficients includes the capacity expansion cost the domestic and international manufacturing facilities multiplied by a coefficients that is either zero or one, representing if the capacity expansion occurs or not.

Definition 3: In order to calculate the total increase in the objective function for the relaxed problem by producing one unit at either domestic or international manufacturing facilities, we form $\sum_k \psi_{jk}, \forall j$ and $\sum_k \varpi_{j'kt}, \forall j^I, t$, $\sum_k \lambda_{jk}, \forall j$ and $\sum_k \mu_{j'kt}, \forall j^I, t$. The summation results are then sorted ascendingly and put into the following four vectors $\theta j, \theta jI, \vartheta j$ and ϑjI for each period, where θj^n represents the increase in the relaxed objective function by one unit production at the domestic plant which corresponds to the n_{th} position of the sorted vector, below its maximum available capacity, ϑj^n represent the increase in the relaxed objective function by one unit production at the domestic plant which corresponds to the n_{th} position of the second sorted vector over its maximum available capacity, θjI_t^m represent the increase in the relaxed objective function by one unit production at the international plant which corresponds to the m_{th} position of the sorted vector below its maximum available capacity in each period *t*, and finally ϑjI_t^m represent the increase in the relaxed objective function by one unit production at the international plant which corresponds to the m_{th} position of the second sorted vector over its maximum available capacity in each period *t*.

It should be noted that the parameters addressing the domestic plants are independent of the planning period, whereas the parameters related to the international plants should be calculated for each planning period individually due to the exchange rate factor which is assumed to be different for each period. Of course other parameters can also change over time if needed, based on the problem and can simply be added in the analytical model.

Throughout the following section all the variables with superscript *n* or *m*, represent the associated parameters which correspond to the n_{th} or m_{th} position or rank in the sorted vectors. We assume the total planned production level in each period to be a function of the expected demand and the minimum accepted expected average service level for each period $(D = \mu \times \varepsilon)$, and also assume $X^n = 1$, if $D \in \left[Cap\max j^{n-1}, Cap\max j^n\right]$. First we discuss the managerial insights based on the special cases of the analytical model and then present the more general form to define the first-stage decisions analytically.

4.2.1. In-house production

Based on the above mentioned definitions, we obtain some practical managerial insights which help managers decide on the possible production, capacity expansion and outsourcing alternatives. In this section we analyze the case where it's more profitable not to outsource the production.

Proposition 1: Given a set of domestic manufacturing facilities j, a set of manufacturing facilities at international locations j^I, a set of identical distribution centers k or a centralized distribution center and a group of customer zones l, it is more profitable to produce domestically if $\theta jI_t^1 \geq \vartheta j^n$ for all n in each period t.

proof: Parameter θjI_t^1 corresponds to the first rank in the sorted vector for each period, representing the international plant j^I causing the least increase in the relaxed objective function, and thus incurring the least costs excluding the capacity expansion costs, and the first candidate among other international manufacturing facilities for outsourcing. Also parameter ϑj^n corresponds to sorted vector for the domestic plants including the capacity expansion costs. If $\theta jI_t^1 \geq \vartheta j^n$ for all n in each period t, it means that the best candidate in the set of international manufacturing facilities even without including the capacity expansion costs makes more increase in the relaxed objective function, comparing to all the domestic manufacturing facilities including the capacity expansion costs. In this case the managers should produce domestically and expand the capacity at the domestic plants if needed, instead of outsourcing.

Lemma 1: If $\theta j I_t^1 \geq \vartheta j^n$ for all *n* and each *t*, and $\theta j^n \geq \vartheta j^1$ for some *n*, it is possible that the optimal solution suggests expanding the capacity of one of the domestic plants, even if the total planned production quantity does not exceed the total available capacity at all the domestic plants.

proof: Based on proposition 1, the total production should be done domestically and since $\theta j^n \geq \vartheta j^1$ for some *n*, there exist some plants in which the undercapacity operating costs are greater than the overcapacity operating costs at some other plants, as the result in case the total planned production amount has not been satisfied up to that point, the optimal solution suggests expanding the facility which corresponds to ϑj^1 until the planned production level is satisfied, instead of producing in the next plant in the sorted vector θj^n.

Lemma 2: If $\theta j I_t^1 \geq \vartheta j^n$ for all *n* in each period *t*, and $\theta j^J \leq \vartheta j^1$, no capacity expansion is done at any of the domestic plants unless the total planned production quantity exceeds the total available capacity at all the domestic plants.

proof: Based on proposition 1, the total production should be done domestically and since $\theta j^J \leq \vartheta j^1$, the undercapacity operating costs at the last plant in the sorted vector θj^J which causes the greatest increase in the relaxed objective function, is less than the overcapacity operating costs of the first plant in the sorted vector ϑj^1, thus the capacity of none of the facilities is expanded, unless the total planned production quantity exceeds the total available capacity at all domestic plants. In this case the plant corresponding to ϑj^1 will be selected for expansion until the planned production level is reached.

Lemma 3: If $\theta j l_t^1 \geq \vartheta j^n$ for all n and each t, $\theta j^J \leq \vartheta j^1$ and $\sum_{n=1}^{J} Cap\max j^n \geq D$, the total first-stage costs are calculated as:

$$\sum_{n=1}^{J} \theta j^{n-1} X^n + \frac{D^n - Cap\max j^{n-1} X^n}{Cap\max j^n - Cap\max j^{n-1}} (\theta j^n - \theta j^{n-1}). \tag{43}$$

proof: Based on proposition 1, all the production should be done domestically and since $\sum_{n=1}^{J} Cap\max j^n \geq D$ based on lemma 2 it is more profitable not to expand the available capacity of the domestic plants. The total first-stage costs are modeled as a piece-wise linear function depending the total available capacity of the domestic plants and the total planned production amount. Based on proposition 1 and lemma 2, the first candidate for production is the domestic plant corresponding to θj^1 and since no capacity expansion is necessary, the production is done in the following plants in the sorted vector until the planned level is reached. In order to calculate the first-stage costs, for each domestic plant j and planning period t we have:

$$X^n = \begin{cases} 1, \text{ if } D \in \left[Cap\max j^{n-1}, Cap\max j^n\right], \text{ and } \sum_{n=1}^{J} X^n = 1 \\ 0, \text{ otherwise;} \end{cases} \tag{43a}$$

$$Cap\max j^{n-1} X^n \leq D^n \leq Cap\max j^n X^n, \text{ and } D = \sum_{n=1}^{J} D^n \tag{43b}$$

Finally based on Figure 5 the total first-stage cost is calculated in (43).

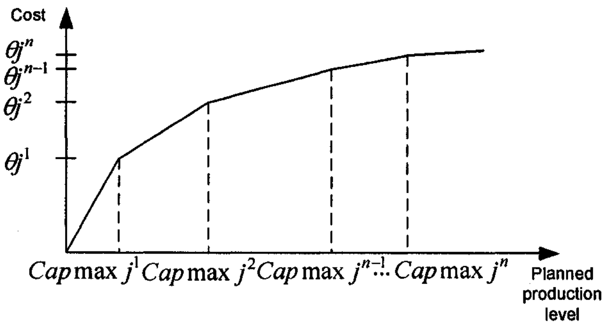

Figure 5 First-stage costs (Lemma 3)

Lemma 4: If $\theta jI_t^1 \geq \vartheta j^n$ for all n in each period t, $\theta j^J \leq \vartheta j^1$ and $\sum_{n=1}^{J} Cap\max j^n \leq D$, the total first-stage costs are calculated as:

$$\sum_{n=1}^{J} Cap\max j_j^n \times \theta j^n + (D - \sum_{n=1}^{J} Cap\max j_j^n)\vartheta j^1 \tag{44}$$

proof: Based on proposition 1 and lemma 2, capacity expansion is done only after the available capacity at all the domestic plants has been used. The rest of the production is done at the plant corresponding to the first place in the sorted vector ϑj^n until the planned production level is reached.

4.2.2. Full outsourcing

Here we analyze the case where it is more profitable to outsource the whole manufacturing.

Proposition 2: Given a set of domestic manufacturing facilities j, a set of manufacturing facilities at international locations j^I, a set of identical distribution centers k or a centralized distribution center and a group of customer zones l, it is more profitable to outsource the whole production to the international manufacturing facilities if $\theta j^1 \geq \vartheta jI^m$ for all m.

proof: Parameter θj^1 corresponds to the first rank in the sorted vector, representing the domestic plant j causing the least costs excluding the capacity expansion costs. The parameter ϑjI^m corresponds to sorted vector for the international plants including the capacity expansion costs. If $\theta j^1 \geq \vartheta jI^m$ for all m, it means that the best candidate in the set of domestic manufacturing facilities even without including the capacity expansion costs makes more increase in the relaxed objective function, comparing to all the international manufacturing facilities including the capacity expansion costs. In this case the managers should decide to outsource the whole production.

Lemma 5: If $\theta j^1 \geq \vartheta jI^m$ for all m and $\theta jI^m \geq \vartheta jI^1$ for some m, it is possible that the optimal solution suggests expanding the capacity of one of the international plants, even if the total planned production quantity does not exceed the total available capacity at all the international plants.

proof: We take the same procedure as the proof of lemma 1.

Lemma 6: If $\theta j^1 \geq \vartheta jI^m$ for all m, and $\theta jI^{J'} \leq \vartheta jI^1$, no capacity expansion is done at any of the international plants unless the total planned production quantity exceeds the total available capacity at all the international plants.

proof: We take the same procedure as the proof of lemma 2.

Lemma 7: If $\theta j^1 \geq \vartheta jI^m$ for all m, $\theta jI^{J'} \leq \vartheta jI^1$, and $\sum_{m=1}^{J'} Cap\max jI^m \geq D$ the total first-stage costs are calculated as:

$$\sum_{m=1}^{J'} \theta jI^{m-1} X^m + \frac{D^m - Cap\max jI^{m-1} X^m}{Cap\max jI^m - Cap\max jI^{m-1}} (\theta jI^m - \theta jI^{m-1}). \tag{45}$$

proof: We take the same procedure as the proof of lemma 3.

Lemma 8: If $\theta j^1 \geq \vartheta jI^m$ for all *m*, $\theta jI^{J^I} \leq \vartheta jI^1$ and $\sum_{m=1}^{J^I} Cap \max j^m \leq D$ the total first-stage costs are calculated as:

$$\sum_{m=1}^{J^I} Cap \max jI^m \times \theta jI^m + (D - \sum_{m=1}^{J^I} Cap \max jI^m)\vartheta jI^1 \tag{46}$$

proof: We take the same procedure as the proof of lemma 4.

4.2.3. Global and domestic production

In the last section we analyze the case where the optimal solution suggests both in-house production and outsourcing.

Proposition 3: Given a set of domestic manufacturing facilities j, a set of manufacturing facilities at international locations j^I, a set of identical distribution centers k or a centralized distribution center and a group of customer zones l, it is more profitable to prioritize domestic production, and then global production to satisfy the planned production level, if $\theta j^1 \leq \theta jI^m \leq \vartheta j^1$ for all *m*.

proof: Since, $\theta j^1 \leq \theta jI^m$ the priority of production is with the domestic plants, and as $\theta jI^m \leq \vartheta j^1$, it is more profitable to outsource the production instead of expanding the capacity at the domestic plants if the planned production level has not been satisfied up to that point.

Lemma 9: If $\theta j^1 \leq \theta jI^m \leq \vartheta j^1$ for all *m* and $D \leq \sum_{n=1}^{J} Cap \max j^n + \sum_{m=1}^{J^I} Cap \max jI^m$ it is never optimal to expand the capacity at the domestic plants.

proof: In case of lemma 1 since $\theta jI^m \leq \vartheta j^1$ even if the panned level does not exceed the available capacity, it is more profitable to outsource the production to the international manufacturing facilities comparing to capacity expansion at the domestic plants. In case of lemma 2 even if the panned production level exceeds the available capacity, for the same reason outsourcing is more profitable, thus there is never the case to expand the capacity at the domestic plants.

Lemma 10: If $\theta j^{n} \leq \theta jI^{m} \leq \vartheta j^{1}$ for all *n* and *m*, $\theta j^{J} \leq \vartheta j^{1}$ and $D \leq \sum_{n=1}^{J} Cap \max j^{n}$ the total first-stage costs are calculated as:

$$\sum_{n=1}^{J} \theta j^{n-1} X^{n} + \frac{D^{n} - Cap \max j^{n-1} X^{n}}{Cap \max j^{n} - Cap \max j^{n-1}} (\theta j^{n} - \theta j^{n-1}) . \tag{47}$$

proof: Based on proposition 3 the production should be first done at the domestic plants, and based on lemma 2 and the fact that the available capacity satisfies the planned production level, there is neither the need for capacity expansion, nor outsourcing. Thus the total first-stage costs are calculated based on lemma 3.

Lemma 11: If $\theta j^{n} \leq \theta jI^{m} \leq \vartheta j^{1}$ for all *n* and *m*, $\theta j^{J} \leq \vartheta j^{1}$, $\theta jI^{J'} \leq \vartheta jI^{1}$ and $\sum_{n=1}^{J} Cap \max j^{n} \leq D \leq \sum_{n=1}^{J} Cap \max j^{n} + \sum_{m=1}^{J'} Cap \max jI^{m}$ the total first-stage costs are calculated as:

$$\begin{aligned} &\sum_{n=1}^{J} Cap \max j^{n} \times \theta j^{n} + \sum_{m=1}^{J'} \theta jI^{m-1} X^{m} \\ &+ \frac{D^{m} - Cap \max jI^{m-1} X^{m}}{Cap \max jI^{m} - Cap \max jI^{m-1}} (\theta jI^{m} - \theta jI^{m-1}) \end{aligned} \tag{48}$$

proof: Based on proposition 3 the production is first done at the domestic plants and based on lemma 9 since the available capacity at the domestic plants is not enough to satisfy the planned production level, the rest of the production should be outsourced which is less than the total available capacity at the international manufacturing facilities. As the result the rest of the total first-stage costs are calculated considering lemma 7.

Lemma 12: If $\theta j^n \le \theta jI^m \le \vartheta j^1$ for all n and m, $\theta j^J \le \vartheta j^1$, $\theta jI^{J^I} \le \vartheta jI^1$ and $D \ge \sum_{n=1}^{J} Cap\max j^n + \sum_{m=1}^{J^I} Cap\max jI^m$ the total first-stage costs are calculated as:

$$\begin{gathered}\sum_{n=1}^{J} Cap\max j^n \times \theta j^n + \sum_{m=1}^{J^I} Cap\max jI^m \times \theta jI^m \\ + \min(\vartheta j^1, \vartheta jI^1) \times (D - (Cap\max j^n + Cap\max jI^m))\end{gathered} \tag{49}$$

proof: Based on proposition 3 the production is first done at the domestic plants and then based lemma 9 at the international plants. As the planned production level exceeds the total available capacity at both domestic and international manufacturing facilities, the rest of the production is done at the facility which leads to the least capacity expansion costs.

Proposition 4: Given a set of domestic manufacturing facilities j , a set of manufacturing facilities at international locations j^I, a set of identical distribution centers k or a centralize distribution center and a group of customer zones l, it is more profitable to prioritize outsourcing and then the domestic production to satisfy the planned production level, if $\theta jI^1 \le \theta j^n \le \vartheta jI^1$ for all n.

proof: We take the same procedure as the proof of proposition 3.

Lemma 13: If $\theta jI^1 \le \theta j^n \le \vartheta jI^1$ for all n, and $D \le \sum_{n=1}^{J} Cap\max j^n + \sum_{m=1}^{J^I} Cap\max jI^m$ it is never optimal to expand the capacity at the international plants.

proof: In case of lemma 5 since $\theta j^n \le \vartheta jI^1$ even if the panned level does not exceed the available capacity, it is more profitable to produce domestically comparing to capacity expansion at the international plants. In case of lemma 6 even if the panned level exceeds the available capacity, for the same reason domestic production is more profitable, thus there is never the case to expand the capacity at the international plants.

Lemma 14: If $\theta jI^m \le \theta j^n \le \vartheta jI^1$ for all n and m, $\theta jI^{J'} \le \vartheta jI^1$ and $D \le \sum_{m=1}^{J'} Cap\max jI^m$ the total first-stage costs are calculated as:

$$\sum_{m=1}^{J'} \theta jI^{m-1} X^m + \frac{D^m - Cap\max jI^{m-1} X^m}{Cap\max jI^m - Cap\max jI^{m-1}} (\theta jI^m - \theta jI^{m-1}) \tag{50}$$

proof: Based on proposition 4 the production should be first done at international plants and based on lemma 6 and the fact that the available capacity satisfies the planned production level, there is neither the need for capacity expansion, nor domestic production. Thus the total first-stage costs are calculated based on lemma 7.

Lemma 15: If $\theta jI^m \le \theta j^n \le \vartheta jI^1$ for all n and m, $\theta j^J \le \vartheta j^1$, $\theta jI^{J'} \le \vartheta jI^1$ and $\sum_{m=1}^{J'} Cap\max jI^m \le D \le \sum_{n=1}^{J} Cap\max j^n + \sum_{m=1}^{J'} Cap\max jI^m$ the total first-stage costs are calculated as:

$$\begin{aligned} &\sum_{m=1}^{J'} Cap\max jI^m \times \theta jI^m + \sum_{n=1}^{J} \theta j^{n-1} X^n + \\ &\frac{D^n - Cap\max j^n X^n}{Cap\max j^n - Cap\max j^{n-1}} (\theta j^n - \theta j^{n-1}) \end{aligned} \tag{51}$$

proof: Based on proposition 4 the production is first done at the international plants and based on lemma 13 since the available capacity at the international plants is not enough to satisfy the planned production level, the rest of the production should be done domestically which is less than the total available capacity at the domestic manufacturing facilities. As the result the rest of the total first-stage costs are calculated considering lemma 3.

Lemma 16: If $\theta j^{n} \leq \theta jI^{n} \leq \vartheta j^{1}$ for all n, $\theta j^{J} \leq \vartheta j^{1}$, $\theta jI^{J^{I}} \leq \vartheta jI^{1}$ and $D \geq \sum_{n=1}^{J} Cap\max j^{n} + \sum_{m=1}^{J^{I}} Cap\max jI^{m}$ the total first-stage costs are calculated as:

$$\begin{aligned}&\sum_{n=1}^{J} Cap\max j^{n} \times \theta j^{n} + \sum_{m=1}^{J^{I}} Cap\max jI^{m} \times \theta jI^{m} \\ &+ \min(\vartheta j^{1}, \vartheta jI^{1}) \times (D - (Cap\max j^{n} + Cap\max jI^{m}))\end{aligned} \tag{52}$$

proof: Based on proposition 4 the production is first done at the international plants and then based lemma 13 at the domestic plants. As the planned production level exceeds the total available capacity at both domestic and international manufacturing facilities, the rest of the production is done at the facility which leads to the least capacity expansion costs.

Lemma 17: Any manufacturing facility that is selected for production should produce at least to its maximum available capacity, unless the planned production level has been met.

proof: When a manufacturing facility is selected, it means it has the best operating costs at that point so the managers should take advantage of production at that operating cost level, before the expansion costs incur. Obviously if the planned production level has been met the production should be stopped.

4.3. Algorithm for the proposed analytical framework

As previously mentioned the proposed heuristic method only tackles the first-stage decisions, thus we define the first-stage decisions and let the software decide on the second-stage decisions. As a result we first determine the production, outsourcing and capacity expansion decisions, and input the results as parameters into the software to decide on the stochastic, transportation and logistic decision variables and calculate the total costs. The algorithm for defining the first-stage decisions is presented in the following pseudo code:

```
Step1. Calculate the planned production level based on the expected demand and the minimum accepted expected service level.
Step2. Input unit production costs, unit transportation costs to the distribution center, exchange and tariff rate and the transfer price for the domestic and international manufacturing facilities.
Step3. Calculate coefficients $\sum_k \psi_{jk}, \forall j$, $\sum_k \varpi_{j'kt}, \forall j^I, t$, $\sum_k \lambda_{jk}, \forall j$ and $\sum_k \mu_{j'kt}, \forall j^I, t$.
Step4. Form the sorted vectors $\theta j^n$, $\vartheta j^n$, $\theta j I_t^m$ and $\vartheta j I_t^m$.
Step5. Sort the elements of the sorted vectors $\forall n, m, t$.
Step6. Assign the production to the first element which is $\min(\theta j^n, \theta j I_t^m)$, if the planned production level is met STOP.
Step7. Assign the production to the following elements which represent production in the undercapacity or overcapacity mode at the domestic or international plants.
Step8. If the planned production level is met, STOP; else go to step7.
```

4.4. Comparison of the results of the proposed heuristic method with GAMS optimization software

Here we consider two problems and compare the results obtained from the proposed heuristic method, with the results obtained from the GAMS optimization software [52].

4.4.1. Case 1

We have designed a hypothetical global supply chain consisting of three domestic manufacturing facilities in Canada (plant1-plant3), three international manufacturing facilities in Mexico (Iplant1-Iplant3), one centralized distribution center in Canada (Dcenter), five customer zones in Canada and the US (Czone1-Czone5) and twelve planning periods. The input parameters are given in APPENDIX A as an example, of course the method is not dependant on the input parameters and any country, any cost parameter and any setting can be used in the model. The tariff cost is assumed to be 30% of the total production costs at the international manufacturing facilities, and since the Canadian company does not have any facilities outside Canada, it does not incur any transfer prices between its facilities. The mean demand rate is 100 units per period and the standard deviation is 20% of the mean demand.

It should be noted that we have input the same exchange rates for each period just to avoid repetition of the same calculations for each period; of course changing any of the parameters for each period just requires separate calculations and does not affect the solution procedure or the results of the proposed heuristic method at all. Also all the cost parameters are given in Canadian dollars and do not need to be converted using exchange rates for reach country. Based on the input parameters, the previously discussed coefficients are given in Table 4 and Table 5.

Table 4 Vectors for the domestic plants

Domestic plants	**Corresponding value**
θj^1	33 (Plant3)
θj^2	42 (Plant1)
θj^3	45.25 (Plant2)
ϑj^1	62 (Plant1)
ϑj^2	63 (Plant3)
ϑj^3	65.25 (Plant2)

Table 5 Vectors for the international plants

International plants	**Corresponding value**
θjI^1	38.65 (Iplant1)
θjI^2	43.97 (Iplant2)
θjI^3	54 (Iplant3)
ϑjI^1	48.65 (Iplant1)
ϑjI^2	53.97 (Iplant2)
ϑjI^3	59 (Iplant3)

This case is a combination of the previously mentioned special cases. To start the solution procedure we first compare the first sorted vectors. Based on proposition 3 the priority of production is with the domestic plants. Thus based on lemma 17, plant3 produces up to its maximum available capacity. Then based on lemma 9 capacity expansions is never optimal at the domestic plants, so in the next step Iplant1 produces up to its maximum available capacity and then based on lemma 17 plant1, Iplant2 and plant2 produce within their capacities. At this point based on lemma 5 production never happens at Iplant3, and here the optimal solution suggests expanding at the manufacturing facility corresponding to the $\min(\vartheta j^1, \vartheta jI^1)$, which is Iplant1. The results are valid for each planning period; Of course if any of the parameters change over time, the discussed solution procedure should exactly be repeated for each individual period corresponding to its own parameters and values. The comparison of the results of the proposed heuristic method with the ones obtained from the software is given in Table 6 and Table 7.

Table 6 Results for Case 1 form the heuristic method

First-stage decision variables	$Qj_{plant1,t}$ $\forall t$	$Qj_{plant2,t}$ $\forall t$	$Qj_{plant3,t}$ $\forall t$	$QjI_{Iplant1,t}$ $\forall t$	$QjI_{Iplant2,t}$ $\forall t$	$QjI_{Iplant3,t}$ $\forall t$	**Total Cost**	**Expected average service level**
Values	100	50	100	150	100	0	488726.549	99.5%

Table 7 Results for Case 1 from the software

First-stage decision variables	T=1	T=2	T=3	T=4	T=5	T=6	T=7	T=8	T=9	T=10	T=11	T=12
$Qj_{plant1,t}$	100	249	100	100	392	100	100	100	100	100	100	100
$Qj_{plant2,t}$	50	50	50	50	7	50	50	50	50	50	50	1
$Qj_{plant3,t}$	100	100	100	100	100	100	190	100	100	100	100	100
$QjI_{Iplant1,t}$	145	82	197	147	36	100	154	328	162	100	145	298
$QjI_{Iplant2,t}$	101	21	0	100	12	100	0	1	50	95	100	0
$QjI_{Iplant3,t}$	0	0	0	0	0	0	0	3	0	0	0	0
Total Cost	499836.689											
Expected average service level	99.5%											

As it is shown from the results, the proposed heuristic method has resulted in 2.22% decrease in the total costs, with the same expected average service level comparing to the software.

4.4.2. Case 2

The hypothetical setting of the second case is the same as the first case. The input parameters of case 2 are given in APPENDIX B. Based on the input parameters, the previously discussed coefficients are given in Table 8 and Table 9.

Table 8 Vectors for the domestic plants

Domestic plants	**Corresponding value**
θj^1	38 (plant3)
θj^2	42 (plant1)
θj^3	45.25 (plant2)
ϑj^1	48 (plant3)
ϑj^2	62 (plant1)
ϑj^3	65.25 (plant2)

Table 9 Vectors for the international plants

International plants	**Corresponding value**
θjI^1	32.15 (Iplant1)
θjI^2	47.5 (Iplant3)
θjI^3	50.47 (Iplant2)
ϑjI^1	52.15 (Iplant1)
ϑjI^2	53.5 (Iplant3)
ϑjI^3	60.47 (Iplant2)

We take the same solution procedure as case 1. To start the solution procedure we first compare the first sorted vectors. Based on proposition 4 the priority of production is with the international plants. Thus based on lemma 17, Iplant1 produces up to its maximum available capacity. Based on lemma 13 capacity expansions is never optimal at the international plants, so in the next step plant3 produces up to its maximum available capacity and then based on lemma 17 plant1 and plant2 produce within their capacities. At this point based on lemma 5 production never happens at Iplant2, and here the optimal solution suggests expanding the manufacturing facility corresponding to the $\min(\vartheta j^1, \vartheta jI^1)$, which is plant3.

Again the results are valid for each planning period; Of course if any of the parameters change over time, the discussed solution procedure should exactly be repeated for each individual period corresponding to its own parameters and values. The comparison of the results of the proposed heuristic method with the ones obtained from the software is given in Table 10 and Table 11.

Table 10 Results for Case 2 form the heuristic method

First -stage decision variables	$Qj_{plant1,t}$ $\forall t$	$Qj_{plant2,t}$ $\forall t$	$Qj_{plant3,t}$ $\forall t$	$QjI_{Iplant1,t}$ $\forall t$	$QjI_{Iplant2,t}$ $\forall t$	$QjI_{Iplant3,t}$ $\forall t$	**Total Cost**	**Expected average service level**
Values	50	50	125	100	0	100	464410.979	85%

Table 11 Results for Case 2 from the software

First-stage decision variables	T=1	T=2	T=3	T=4	T=5	T=6	T=7	T=8	T=9	T=10	T=11	T=12
$Qj_{plant1,t}$	0	50	3	49	50	0	50	50	0	50	50	0
$Qj_{plant2,t}$	0	41	2	50	50	30	0	50	0	50	50	0

$Qj_{plant3,t}$	310	195	330	207	294	222	401	212	450	6	233	433
$QjI_{Iplant1,t}$	100	100	100	100	68	100	100	268	0	268	100	35
$QjI_{Iplant2,t}$	0	0	0	0	0	0	6	0	0	0	0	0
$QjI_{Iplant3,t}$	0	0	0	0	0	0	0	0	0	0	0	0
Total Cost	468980.272											
Expected average service level	85%											

As it is shown from the results, the proposed heuristic method has again resulted in a decrease in the total costs, with the same expected average service level comparing to the software.

4.5. General model and managerial insights

4.5.1. Experimental design

In this section we go back to the original model discussed in the previous chapter.

In order to study the applicability of the proposed model, we consider a hypothetical network setting. The network addresses a Canadian company which has three manufacturing plants in Toronto, Calgary and Montreal and two distribution centers in Vancouver and Toronto. The main customer zones are Toronto, Halifax, Seattle, Chicago and Los Angeles. The company has the option of outsourcing its production to three candidate manufacturing plants in Mexico in Monterrey, Mexico City and Guadalajara, and distributing through two candidate distribution centers in the US in Los Angeles and Houston. Any country can be selected based on its corresponding exchange and tariff rates.

We consider three transportation modes of rail, truck and a combination of the two transportation modes. Again any transportation mode can be adopted in our model based the transportation cost and lead-time of each mode. We consider a single product without specifying its type, as our main goal is to keep our model general so that it can easily be adapted to different situations [46]. The tool to adjust the proposed model to different supply chain and product types are the target service level, transportation mode selection with shorter or longer lead-times, and the possibility of overstocking or losing the customer order. In the following examples we have assumed that the overstocked items are disposed or sold at lower prices in the following periods. The analysis for the nonperishable items is given individually in cases 15 and 16. Our model is one of the few practical models which can conveniently be customized for various real world supply chains.

We have made some assumptions throughout the cases studied in this research. First of all we only consider tactical level decisions, and also the size of the facilities are small enough that can be either used or not at each planning period meaning that there is no long-term contract or ownership of the international facilities. There is no restriction on the number of facilities serving each distribution center or customer zone.

The example is adequate and shows the usefulness of the model. Most of the input data on the transportation costs, transportation modes and the associated lead-times have been derived from Bookbinder and Fox [4]. It should be noted that in general all the studied cases are hypothetical and based on the input parameters and the assumption of zero initial inventory, lost sale and overstock levels.

The common input parameters for both the cases with continuous stochastic variables and discrete stochastic variables are given in APPENDIX C. The other specific parameters for the two cases are given separately. In the next section we present the numerical example and analysis for the case with continuous stochastic variables, and then for the case with discrete stochastic variables.

4.5.2. Numerical examples for the case with continuous stochastic variables

In this section we consider the case with continuous stochastic variables following a normal distribution. The mean demand rate is assumed to be 100 units per period with the standard deviation of 20% of the mean demand. Of course different mean demand rates with any standard deviation can be chosen for each planning period easily.

4.5.2.1. Cases 3-5

We assume that the manager of the above mentioned hypothetical company wants to decide on the expansion of its existing facilities, or outsourcing to the potential international plants. We consider three general cases and then present our results and observations: Case 3) in the third case which is the base case we assume that the company has the option of outsourcing its production to international manufacturing facilities, Case 4) in the fourth case it is assumed that the entire manufacturing is outsourced and thus there is no in-house production, Case 5) and in the fifth case it is assumed that all the production should be done domestically. All the cases are considered in 12 planning periods which is sufficient in order to maintain feasibility with respect to the transportation lead-times.

The result of the base case is given in APPENDIX D and the comparisons of the results are given in Table 12 and Table 13.

Table 12 Comparison of the objective function values (Cases 3-5)

Case	**Total Cost**	**% Change in the total cost**	**Maximum possible average service level**	**% Change in average service level**
Base case	364168.033	N/A	94.7%	N/A
Full outsourcing	1267425.718	248% increase	70.6%	25% decrease
No outsourcing	534487.030	47% increase	94.6%	0.001% decrease

Table 13 Comparison of the costs (Cases 3-5)

Case	**Total Lost sale cost**	**Total Overstock cost**	**Total Production costs**	**Total Transportation costs**	**Total Inventory costs**	**Total Capacity expansion costs**
Base case	78159.974	12428.749	30232.198	176345.772	4255.342	52366.887
Full outsourcing	201297.627	23854.794	5288.342	1010512.378	804.517	3457.025
No outsourcing	77925.318	12909.489	42362.278	254052.941	13712.868	115444.871

Based on the results, case 3 has the lowest total costs while case 4 incurs the highest total costs. The solution suggests serving a large portion of the Canadian distribution centers and customers from the Canadian plants and distribution centers, and two of the three customer zones in The US, Seattle and Chicago, would also be served from Canadian distribution centers, Vancouver and Toronto respectively. As a result when the company outsources the whole manufacturing to Mexico, despite the fact that manufacturing costs decrease by 83% and capacity expansion costs decrease by 93% due to larger available capacity and lower capacity expansion costs in Mexico, transportation costs, lost sale cost and overstock cost increase by 473%, 156% and 92%

respectively.

The reason is that in order to serve the Canadian customers from international manufacturing facilities, products should be sent to Canadian distribution centers, which results in much larges transportation costs comparing to the base case. Also based on the longer lead-times to the distribution centers, the stochastic sales to the customers can not be done sooner than period 2, which results in the decrease in the expected average service level and complete lost sales in the first period.

Case 5 suggests entire in-house production and results in 47% increase in the total costs. Again the reason is that the optimal solution suggests serving the distribution centers in the US from the Mexican international plants as a result when the company stops outsourcing its production, transportation costs increase by 44%. Production and capacity expansion costs also increase by 40% and 120% respectively, due to higher production and capacity expansion costs and lower available capacity at the Canadian plants comparing to the Mexican ones.

Finally based on this specific example, the case in which the company has the option of both in-house production and outsourcing simultaneously, incurs the least total costs, and the best expected average service level.

4.5.2.2. Case 6

In case 6 we intend to study the effects of increase in demand on the total costs and outsourcing policies. The results are presented in Table 14.

Table 14 Increase in mean demand (Case 6)

Change in mean demand	**Change in Total cost**	**Change in total domestic manufacturing amount**	**Change in total international Manufacturing amount**
0.25	0.128946976	0.0246	0.63906
0.5	0.453926052	0.118	1.28351
0.75	1.103972776	0.305	1.62604
1	1.749860409	0.4879	1.97473
1.25	2.403807068	0.6673	2.32868
1.5	3.065131542	0.8472	2.68262
1.75	3.718685132	1.0271	3.03808

As it is shown in Figure 6 in case of increase in demand, the reliance on outsourcing increases whereas the reliance on in-house production decreases. Also due to the presence of economies of scale the increase in the total costs is less than the increase in the mean demand up to some point, but after some degree of increase in the mean demand the increase in the total costs is far more, as more capacity expansion is needed to fulfill the demand.

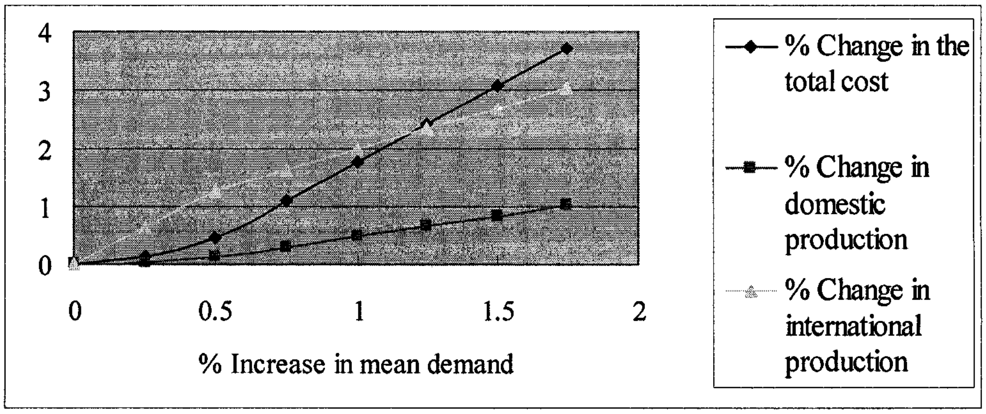

Figure 6 Increase in mean demand (Case 6)

4.5.3. Numerical example for the case with continuous stochastic variables

In this section we consider the case with discrete stochastic variables. The same hypothetical setting as the previous section with the common parameters given in APPENDIX C has been adopted. The specific input parameters for the discrete case are given in APPENDIX E.

4.5.3.1. Cases 7-9

In cases 7-9 again we consider the case that the decision maker wants to decide on the expansion of its existing facilities, or outsourcing to the potential international plants. Cases 7-9 consider the base case, full outsourcing and in-house production respectively. The result of the base case is given in APPENDIX F and the comparison of the results is given in Table 15 and Table 16.

Table 15 Comparison of the objective function values (Cases 7-9)

Case	**Total Cost**	**% Change in total cost**	**Maximum possible average service level**	**% Change in average service level**
Base case	1285507.249	N/A	91.7%	N/A
Full outsourcing	1338175.409	4% increase	68.3%	26% decrease
No outsourcing	1618258.443	26% increase	91.7%	0%

Table 16 Comparison of the costs (Cases 7-9)

Case	**Total Lost sale cost**	**Total Overstock cost**	**Total Production costs**	**Total Transportation costs**	**Total Inventory costs**	**Total Capacity expansion costs**
Base case	257708.542	34840.035	68176.017	701131.799	7094.885	179945.266
Full outsourcing	521000	63166.667	8297.393	696119.133	659.527	14083.638
No outsourcing	265899.840	39450.186	117545.758	789103.906	1561.026	320209.905

As it is shown in the results, case 7 which is the base case, results in the least costs. The reason is that the company has more power and flexibility in choosing the right manufacturing facilities which are conveniently located closer to each of the distribution centers in order to reduce the transportation costs and also can also benefit from the lower production costs at the international plants at the same time. Cases 8 and 9 which represent exclusively producing at either international or domestic plants, lead to higher costs for the same reasons previously discussed for cases 4 and 5.

4.5.3.2. Case 10

In case 10 we consider the effects of increase in the demand scenarios on the total costs and the extent the company relies on in-house or international manufacturing. The comparison of the results is given in Table 17.

Table 17 Increase in mean demand (Case 10)

Change in demand scenarios	**Change in Total cost**	**Change in total domestic manufacturing**	**Change in international manufacturing**
0.2	0.213308786	0.2324985	0.2324985
0.6	0.629348209	0.66470391	0.66470391
0.8	0.840702413	0.88634726	0.88634726
1	1.043858363	1.08739915	1.08739915
1.2	1.251853771	1.30338153	1.30338153
1.4	1.459934319	1.51792746	1.51792746
1.6	1.671563076	1.73161346	1.73161346
2	2.086660698	2.1627947	2.1627947

As it is shown in Figure 7 in case of increase in demand, the reliance on outsourcing increases whereas the reliance on in-house production decreases. Also due to the presence of economies of scale, the increase in the total costs is less than the increase in the mean demand up to some point, but after some degree of increase in mean demand the increase in the total costs is far more, as more capacity expansion is needed to fulfill the demand.

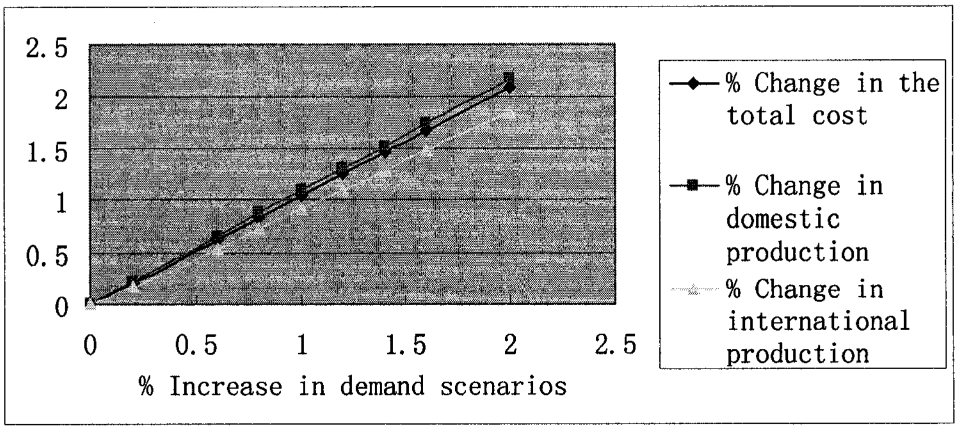

Figure 7 Increase in demand scenarios (case 10)

4.5.4. Lost sale and overstocking policies

In this section we intend to consider the effects of increase in the lost sale or overstocking penalties on the expected average service level, total costs and production amounts at the domestic and international manufacturing facilities.

4.5.4.1. Case 11

In the base case the initial lost sale penalty is twice as much as the overstocking cost. The minimum accepted service level for this case has been set to 90%. The lost sale penalty is then increased and the results are presented in Table 18.

Table 18 Increase in lost sale penalty (Case 11)

Change in unit lost sale penalty	**Change in Total cost**	**Change in the expected service level**	**Change in total domestic manufacturing**	**Change in international manufacturing**
0.5	0	0	0	0
1	0.023379	0.002222	-0.18617	0.282267
1.5	0.09648	0.014444	-0.19649	0.369807
2	0.19564	0.023333	-0.17609	0.412964
2.5	0.292066	0.027778	-0.17609	0.412964
3	0.383823	0.031111	-0.14136	0.473944

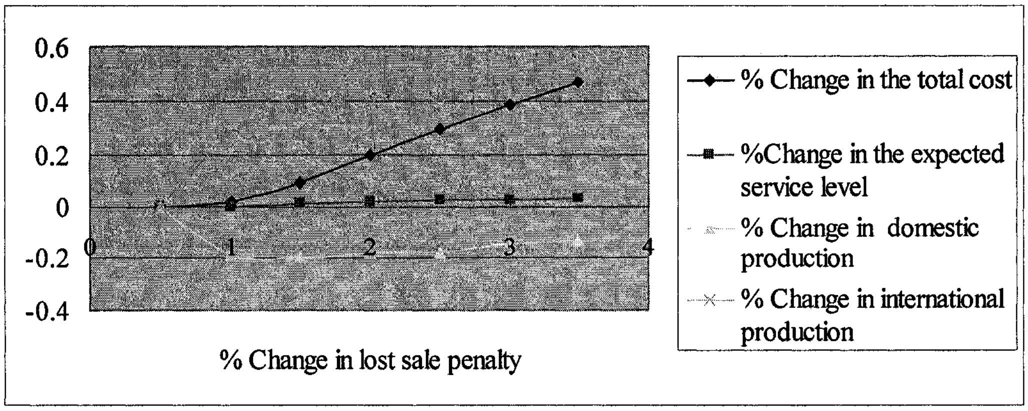

Figure 8 Increase in lost sale penalty

As the results indicate in Figure 8, increasing the penalty on lost sales has led to the increase in the expected service level which means increase in the expected sales to avoid expected lost sales costs. Also the reliance on outsourcing has increased due to lower capacity expansion costs and larger available capacity at the international manufacturing facilities.

4.5.4.2. Case 12

In this section the same analysis is performed considering the overstocking penalty. The initial overstocking cost is half the lost sale penalty. The minimum accepted service level for this case has been set to 90% and then the overstocking cost has been increased. The results are presented in Table 19.

Table 19 Increase in overstocking cost (Case 12)

Change in unit lost sale penalty	**Change in Total cost**	**Change in the expected service level**	**Change in total domestic manufacturing**	**Change in international manufacturing**
0.5	0	0	0	0
1	0.000498	0	0	0
1.5	0.0007	0	0	0
2	-0.0546	0	-0.17	0.25
2.5	-0.0857	0	-0.19	0.27
3	-0.0863	0	-0.19	0.27
3.5	-0.0865	0	-0.19	0.27

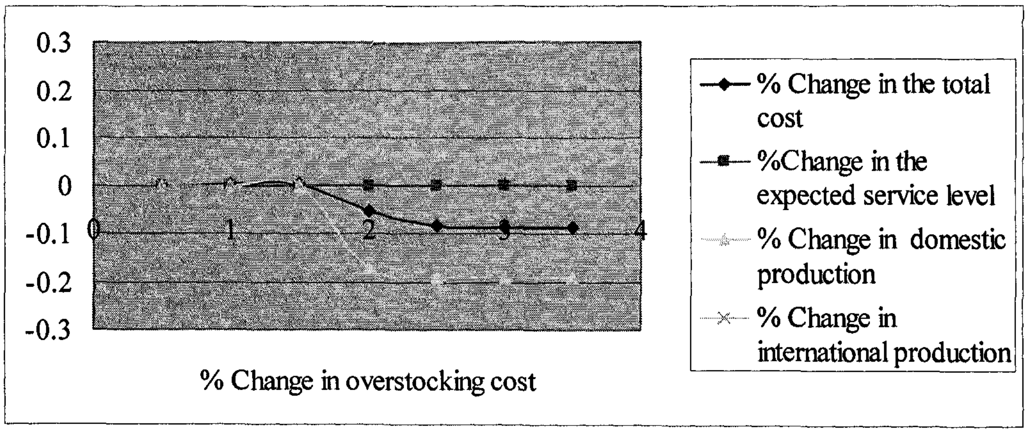

Figure 9 Increase in overstocking cost

Unlike the previous case the service level is not increased and is kept at the minimum acceptable level which is 90%. Based on Figure 9 at first the total cost does not change much due to the increase in the overstocking cost and then as the overstocking cost becomes comparatively bigger than the lost sale cost, the importance of satisfying the demand becomes inferior to the minimization of costs. As a result the solution suggests a shift from domestic production which was previously more important to guarantee the fulfillment of the demand, to international production which leads to less overstocking but more lost sales. After the shift from the domestic production to the international production the solution is not sensitive to the unit overstocking cost any more and the total expected overstocking cost reaches zero.

4.5.5. Transfer price and tariff rate variations

4.5.5.1. Case 13

In this case we observe the effects of increase in transfer prices on the optimal decisions. As previously mentioned transfer prices occur whenever the company is sending products from one of its facilities in one country to another facility in another country. In our model transfer prices only happen when the domestic plants are serving the company's distribution centers in the US. The effects of the increase in transfer prices when the minimum acceptable service level is 90% are shown in Table 20.

Table 20 Increase in transfer prices (case 13)

Change in unit transfer price	Change in Total cost	Change in the expected service level	Change in total domestic manufacturing	Change in international manufacturing
0	0	0	0	0
0.25	-00001361	0	0.0000073	0.000205
0.75	-0.008934803	0	-0.00254427	0.019298
1	-0.008935534	0	-0.00254285	0.019331
1.25	-0.008935827	0	-0.00254653	0.019331
1.5	-0.008950331	0	-0.00254143	0.019373
1.75	-0.008950331	0	-0.00254143	0.019374
2	-0.008950385	0	-0.00254115	0.019374
2.25	-0.008951098	0	-0.0025386	0.019374
2.5	-0.009066256	0	-0.0025386	0.019374
2.75	-0.009066256	0	-0.0025386	0.019374
3	-0.009066256	0	-0.0025386	0.019374

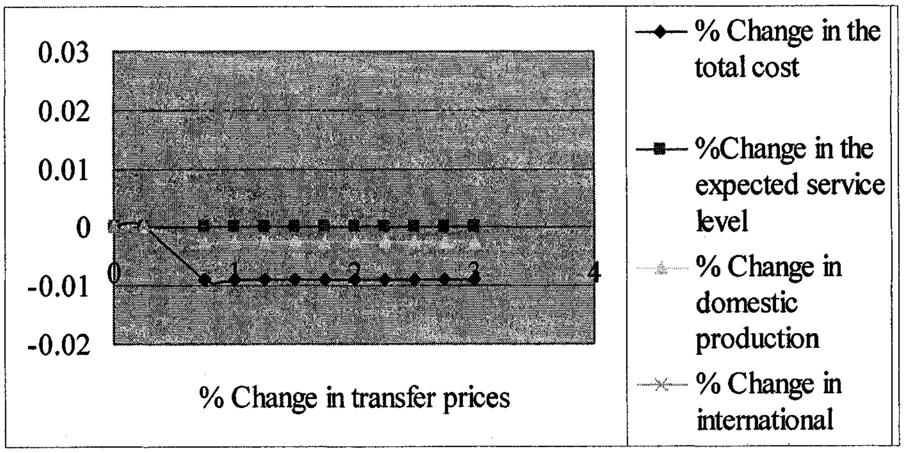

Figure 10 Increase in transfer prices

As it is shown in Figure 10, the service level is kept at the minimum accepted service level and then as a result of the increase in the unit transfer price, it is better not to serve the distribution centers in the US from the domestic plants, so there is a small shift from the domestic production to outsourcing at the beginning to enable the international plants to support the US distribution centers and to satisfy the minimum required service level. Finally there is no change in the total costs and production amounts as the model suggests serving all the distribution centers in the US from international plants and thus there are no further changes in the model.

4.5.5.2. Case 14

This case has been designed to show the effects of increase in the tariff rate on the optimal solution. In our model tariff cost in incurred whenever the production is done internationally and sent to the distribution centers. The comparison of the results is given in Table 21.

Table 21 Increase in tariff rates (case 14)

Change in unit transfer price	**Change in Total cost**	**Change in the expected service level**	**Change in total domestic manufacturing**	**Change in international manufacturing**
0	0	0	0	0
1	0.030141513	0	1.8974E-05	-0.00463
2	0.060099812	0	0.00022741	-0.01404
3	0.089736805	0	0.0057852	-0.02783
4	0.11936634	0	0.00714286	-0.03619
6	0.162632644	0	0.03106785	-0.08122
8	0.189257429	0	0.08076174	-0.1777
9	0.211757582	0	0.08750812	-0.19175

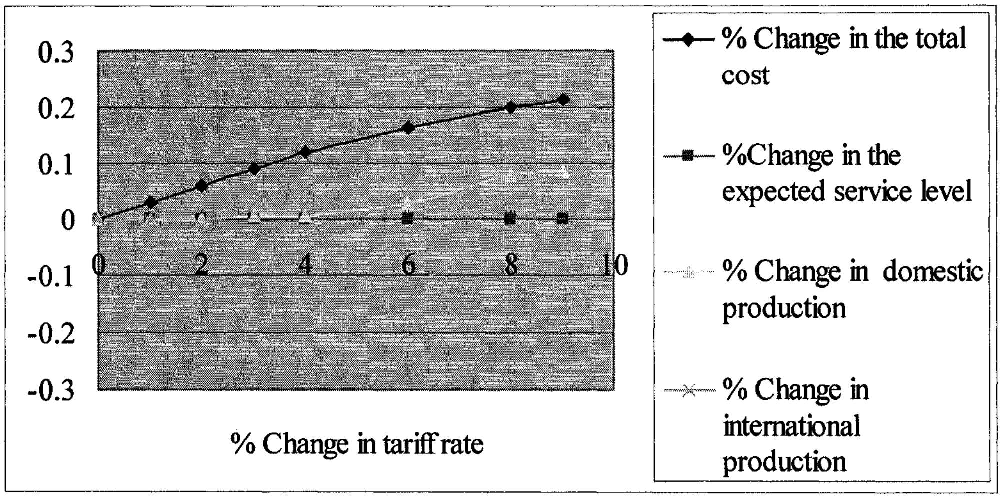

Figure 11 Increase in tariff rates

As it is shown in Figure 11 and intuitively, as the result of the increase in unit tariff rates the production level at the international facilities decrease. The initial tariff rate is around 30% of the international production costs and in the sensitivity analysis it has been increased up to the maximum 300% of the production costs at the international facilities. The increase in the production level at the international facilities never reaches zero since international production is necessary to satisfy the minimum acceptable expected service level.

4.5.6. Perishable and nonperishable products

As it was mentioned in the model development section, the products can be assumed to be perishable or nonperishable. As the result we can either dispose, or use the overstocked items in the upcoming periods. Here we compare the cases where we assume the products are perishable, with the case that the overstocked items can be used to fulfill the upcoming demand for both the cases with continuous and discrete stochastic variables.

4.5.6.1. Case 15

In this case the result obtained from the base case with continuous stochastic variables is compared with same case where the overstocked products are used to satisfy the demand in the current period. As the result we have to adapt the terms given in (1b), (3b) (30a) and (30b). The comparison of the objective function values and the costs are given in Table 22 and Table 23.

Table 22 Comparison of the objective function values (case 15)

Case	**Total Cost**	**% Change in total cost**	**Maximum possible average service level**	**% Change in average service level**
Perishable items	398402.561	N/A	94.6%	N/A
Nonperishable items	317549.979	25% decrease	94.6%	0%

Table 23 Comparison of the costs (case 15)

Case	**Total Lost sale cost**	**Total Overstock cost**	**Total Production costs**	**Total Transportation costs**	**Total Inventory costs**	**Total Capacity expansion costs**
Perishable products	70866.125	21724.007	34801.247	174404.631	4279.744	67780.910
Nonperishable products	62394.031	48023.710	26561.652	112285.148	4431.254	38817.299

As it is shown from the results the case in which the overstocked products can be used to satisfy the demand in the following periods, has resulted in 25% decrease in the total costs with the same expected average service level. The reason is that except for the overstock costs at the customer zones and the inventory costs at the manufacturing and distribution facilities, all the other costs decrease, specially the production and lost sale costs, as the overstocked items in the previous periods, make up for the demand in the upcoming periods. The complete results are given in APPENDIX G.

4.5.6.2. Case 16

In this case the result obtained from the base case with discrete stochastic variables is compared with same case where the overstocked products are used to satisfy the demand in the current period. As the result we have to adapt the terms in (34a), (34b) and (36a). The comparison of the objective function values and the costs are given in Table 24 and Table 25.

Table 24 Comparison of the objective function values (case 16)

Case	Total Cost	% Change in total cost	Maximum possible average service level	% Change in average service level
Perishable products	1280657.622	N/A	88%	N/A
Nonperishable products	1276232.003	0.3%	88%	0%

Table 25 Comparison of the costs (case 16)

Case	Total Lost sale cost	Total Overstock cost	Total Production costs	Total Transportation costs	Total Inventory costs	Total Capacity expansion costs
Perishable products	315241.668	15091.071	69957.231	654185.850	7094.885	189223.594
Nonperishable products	318564.142	103030.195	64574.212	573281.858	8853.747	173851.035

As it is shown from the results again the case in which the overstocked products can be used to satisfy the demand in the following periods, has resulted in increase in the total costs with the same expected average service level. The reason is that except for the overstock costs at the customer zones and the inventory costs at the manufacturing and distribution facilities, all the other costs decrease, as the overstocked products in the previous periods, make up for the demand in the upcoming periods. The complete results are given in APPENDIX H.

4.5.7. Economies of scale in transportation costs

In the following two cases we consider the effects of economies of scale in transportation costs on different decision and cost variables and the objective values. Of course the terms in (10a), (11a) and (12a) should be used to calculate the transportation costs, and also the constraints (27)-(29) should also be considered as well as the other problem constraints for each case with either continuous or discrete stochastic variables. The input parameters for cases 17 and 18 are given in APPENDIX I.

4.5.7.2 Case 17

Here we consider continuous stochastic variables and compare the results of the case which considers the economies of scale in transportation costs, with the base case which does not hold this feature. The comparison of the results is given in Table 26 and Table 27.

Table 26 Comparison of the objective function values (case 17)

Case	Total Cost	% Change in total cost	Maximum possible average service level	% Change in average service level
Absence of economies of scale	398402.561	N/A	94.6%	N/A
Existence of economies of scale	311620.262	22% decrease	94.6%	0%

Table 27 Comparison of the costs (case 17)

Case	**Total Lost sale cost**	**Total Overstock cost**	**Total Production costs**	**Total Transportation costs**	**Total Inventory costs**	**Total Capacity expansion costs**
Absence of economies of scale	70866.125	21724.007	34801.247	174404.631	67780.910	67780.910
Existence of economies of scale	70887.969	21680.887	37377.419	85935.333	690.072	89410.530

Intuitively the existence of economies of scale has led to lower total costs within the same expected service level. In order to take advantage of the economies of scale, the model suggests increasing the production and capacity expansion amount which has led to higher production and capacity expansion costs. On the other hand it has resulted in bigger savings in terms of transportation and inventory costs.

5.5.7.2 Case 18

In this case we intend to consider the effects of increase in the mean demand on the total costs and the extent the company relies on in-house or international manufacturing. The comparison of the results is given in Table 28.

Table 28 Increase in mean demand (Case 18)

% Change in mean demand	**% Change in Total cost**	**% Change in total domestic manufacturing**	**% Change in international manufacturing**
0	0	0	0
0.25	0.274954237	0.28694652	0.21708932
0.5	0.493302119	0.49409096	0.53630171
0.75	0.401112439	0.11903678	2.10796038
1	0.576556356	0.16013484	2.78836289
1.25	0.767469525	0.28834745	3.29196847
1.5	0.922195534	0.29121227	4.05072374
1.75	1.114945524	0.42772684	4.53701492

As it is shown in the results in case of increase in demand the reliance on outsourcing increases more, comparing to the reliance on in-house production. Also due to the presence of economies of scale, the increase in the total costs is less than the increase in the mean demand and this difference becomes larger, as the cost reductions incur in both the transportation and production costs.

5. Conclusions and Recommendations

5.1. Conclusions

In this thesis we designed a practical decision support tool in order to assist managers with tactical level decisions in global supply chains. The proposed model is practical as it can be modified easily to fit any kind of product and any type of supply chain. This is done by considering multiple objectives of minimization of costs and maximization of the expected average service level for all the customers during the planning periods, to act as a tool to adapt the model for both kinds of markets in which the winning criterion is lower costs, and the kind in which the key to success is higher service level. The network we addressed is a global supply chain consisting of domestic and international manufacturing facilities, distribution centers and customer zones. The distribution centers can only be served from the manufacturing plants, and the customers can only be served from the distribution centers.

Outsourcing production to the international manufacturing facilities with higher available capacity, results in lower production and capacity expansion costs whereas domestic production incurs higher production and capacity expansion costs. But considering only the above mentioned facts in the global supply chains, and moving production to the countries with lower labor costs is not always the best case. There are several other factors that should be taken into account in global supply chains comparing to the classic supply chains and failing to consider those factors might lead to wrong decisions.

One of the important factors involved in any global supply chain is the exchange rate factor that affects the favorability of the outsourcing partners. Another issue is that the host country puts some bans on the import of products from other countries, as a result outsourcing production results in tariff costs which should not be neglected. On the other hand if the host company ships from one of its facilities in one country to another facility in another country, it incurs transfer prices.

Transportation costs and lead-times are also one of the deciding factors in outsourcing decisions. In terms of minimization of costs, longer distances form the international plants and longer lead-times, lead to higher transportation and lost sale costs, and in terms of maximization of the expected average service level, they might lead to lost sales and decrease in the customer service level. As the result the relative position and distance of the distribution centers and customer zones to the international plants, and the availability of different transportation modes which give the flexibility of faster deliveries, are very important in outsourcing decisions.

Besides the above mentioned characteristics, another important and unavoidable feature of global supply chains is their uncertain nature. There are several sources of uncertainties in these networks such as demand, exchange rate, delivery and lead-time, etc. from which we have only considered the uncertainty in the demand in this thesis.

In order to solve the multi-objective model we have used the ε-constraint method that keeps the minimization of costs as its main goal, and adds the maximization of the expected average service level as a constraint bounded by some feasible ε which represents the minimum acceptable expected average service level form the decision maker's point of view.

The two-stage stochastic programming method is used to solve the MINLP stochastic model. Based on this method the first-stage decision variables such as production, outsourcing and capacity expansion decisions are made prior to the realization of the uncertain parameter, and the second-stage decisions such as logistics and distribution decisions which address the distribution centers and customer zones, including the expected sales to each customer zone which results in expected lost sale or overstocking costs, are made after the realization of the uncertain variables.

After modeling the global supply chain with the above mentioned characteristics, we simplified the original model to perform more detailed analysis on the first-stage decisions such as production, outsourcing and capacity expansion decisions. The simplifications to make the model more manageable were assuming centralized distribution or identical distribution centers in terms of transportation costs to the customer zones, and identical transportation modes and lead-times. The analytical model holds the rest of the features of the original model which was previously discussed and finally a heuristic solution procedure is proposed to solve the analytical model.

The results of the proposed heuristic have been compared to those of the GAMS commercial software and were observed to obtain better results. Based on the analytical model we have obtained the following managerial insights:

- If the increase in the tariff, production and transportation costs to the distribution center, due to one unit of production at the international plants in the overcapacity mode is less than the same costs at the domestic plants in the undercapacity mode, the optimal solution suggests outsourcing the whole production. On the contrary if the same situation happens for the domestic plants comparing to the international plants, the optimal solution suggests producing domestically (propositions 1 and 2).
- Capacity expansion is not only done when the planned production level exceeds the total available capacity at both the domestic and international plants. This case happens when the operating and shipment costs in the overcapacity mode at some facilities are less than the operating and shipment costs at some other facilities in the undercapacity mode (Lemmas 1 and 5), otherwise capacity expansion is only done when the planned production level exceeds the total available capacity (Lemmas 2 and

6).

- If production is supposed to be done at a facility, it should be done at least to the maximum available capacity at that facility, meaning that after a facility has been selected for operation it is never optimal to stop the production and do the rest at other facilities. Of course this holds true unless the planned production level has been satisfied up to that point of production.

Increase in the transfer prices suggests less shipments to other facilities of the host company which are located at international locations meaning that it is more profitable to serve the facilities that are outside the host country from the international plants which result in lower transportation costs and prevents the occurrence of the transfer prices and tariff costs at the same time.

As the result of increase in tariff rates outsourcing becomes less favorable but sometimes in order to maintain the minimum required service level and to serve the international customers with faster and shorter lead-times, outsourcing is an unavoidable solution.

We will have a decrease in the total costs if the products are not perishable and can be used in the upcoming periods to satisfy the demand. It mostly leads to the decrease in the lost sale and production costs and increase in the overstocking and inventory costs.

5.2. Contributions

With the emergence of multinational companies, lower labor and operating costs in different countries and the diverse types of customers and products all across the globe, classic domestic supply chains can not model a vast number of real world problems.

Due to these facts research in global supply chains is also receiving more attention, but unfortunately there has not been as much work done in this relatively new area comparing to the research on the classic supply chains.

Based on the literature review in this area most of the models consider a specific and complicated feature of the global supply chains whereas a few models provide the decision makers with the practical tools to handle real life problems. A practical and useful model is the one that is flexible enough to address different types of supply chains and product types. On the contrary our model has the ability to handle agile supply chains for lead-time sensitive customers of innovative products, by increasing the minimum accepted expected service level and choosing faster transportation modes causing shorter lead-times. It can also adapt itself to lean supply chains addressing price-sensitive customers for functional products by giving priority to cost reduction comparing to maximizing the expected service level.

Another issue that has not received enough attention in the global supply chain literature is the uncertainty factor which is the integral part of global environments. Our models has covered this issue in both possible situations that there is enough information available about the probability distribution function of the stochastic variables, and the case in which there is not information about this issue, but based on historical data several scenarios can be generated to help model the stochastic variables.

One of main contributions of this thesis was proposing an analytical framework to tackle the first-stage decision variables of some of the special cases of the model. Some simplifications have been made to obtain managerial insights on the production, capacity expansion and outsourcing decisions. Although the analytical model has been simplified, it is still useful for solving large scale problems and providing sub-optimal solutions to facilitate decision making for managers. Of course the commercial software are not able to generate solutions with reasonable computation efforts for large scale problems, and considering the fact that the second-stage variables in our model are non-linear and stochastic, the analytical model can reduce the computation effort of the whole problem by addressing the first-stage decision variables. Also there does not exist much analytical work done on comprehensive global supply chain models, and this work can be a useful stepping stone for future research in this area.

Finally as well as the above mentioned contributions, our model has included some of the most important features of global supply chains including the tariff and exchange rates and transfer prices, considering the fact that not all the previous models in the literature provide a comprehensive, flexible and practical model to solve issues regarding global supply chains.

5.3. Future work

The research outlined in this thesis is one of the few *practical* models comparing to the literature, but like every other research it has its own strengths and shortcomings.

The studied examples are very close to real life problems and are sufficient to depict most of their characteristics, yet there are other real life supply chains that are bigger in size and more complicated. The computation efforts of the commercial software for large scale problems are too much, so a future expansion to this work can be a heuristic method to handle larger instances of the model.

Another issue in our model is that the only uncertain variable is the customer demand which results in stochastic sales, overstock and lost sale costs. Of course several other uncertain factors exist in real life problems and another future expansion to this work can be the inclusion of other uncertain factors such as lead-time, exchange rate and governmental uncertainties, etc. Including more uncertain parameters especially in the discrete case with several realization scenarios, will result in great computation efforts and necessitates using some heuristic methods to handle the large number of scenarios.

In this research we focused on tactical level decisions and included two objectives.

Of course future models can consider operational and strategic decisions as well, and can consider more objectives to make the model more comprehensive and adaptable to real life circumstances.

Finally the proposed heuristic in this thesis tackles a special case of the original model and addresses the first-stage decision variables. Future research based on this work can consider the general case and propose a more comprehensive method to include the second-stage variables as well.

APPENDIX A : Input parameters for case 1

Table 29 First-stage input parameters for case 1

Facility	**Unit production Cost (in Can. dollars)**	**Unit transportation Cost to the distribution center (in Can. dollars)**	**Capacity expansion cost (in Can. dollars)**	**Maximum available capacity**
Plant1	40	2	20	100
Plant2	20	25.25	20	50
Plant3	30	3	30	100
Iplant1	10	25.65	10	100
Iplant2	5	37.47	10	100
Iplant3	10	41	5	100

APPENDIX B : Input parameters for case 2

Table 30 First-stage input parameters for case 2

Facility	Unit production Cost (in Can. dollars)	Unit transportation Cost to the distribution center (in Can. dollars)	Capacity expansion cost (in Can. dollars)	Maximum available capacity
Plant1	40	2	20	50
Plant2	20	25.25	20	50
Plant3	35	3	10	50
Iplant1	5	25.65	20	100
Iplant2	10	37.47	10	100
Iplant3	5	41	5	100

APPENDIX C : Input parameters for the general case

Table 31 Domestic plants

Plant1	Plant2	Plant3
Toronto	Calgary	Montreal

Table 32 International plants

Iplant1	Iplant2	Iplant3
Monterrey	Mexico city	Guadalajara

Table 33 Distribution centers

Dcenter1	Dcenter2	Dcenter3	Dcenter4
Vancouver	Toronto	LA	Houston

Table 34 Customer zones

Czone1	Czone2	Czone3	Czone4	Czone5
Toronto	Halifax	Seattle	Chicago	LA

Table 35 Transportation modes

r1	r2	r3
Rail	Truck	Combination of both

Table 36 First-stage input parameters for the general case

Facility	Capacity expansion cost (in Can. dollars)	Maximum available capacity	Unit inventory holding cost (in Can. dollars)
Plant1	20	100	5
Plant2	20	50	10
Plant3	30	100	8
Iplant1	10	150	10
Iplant2	10	200	7
Iplant3	5	100	6

Table 37 Other input parameters for the general case

Pipe-line inventory cost	Lost sale penalty	Overstock penalty
3	100	50

Table 38 Transfer prices and Tariff rates in Canadian dollars from domestic plants to distribution centers

Origin _ Destination	Transfer prices	Tariff rates
Toronto _ Vancouver	0	0
Toronto _ Toronto	0	0
Toronto _ LA	20	0.2
Toronto _ Houston	20	0.2
Calgary _ Vancouver	0	0
Calgary _ Toronto	0	0
Calgary _ LA	20	0.2
Calgary _ Houston	20	0.2
Montreal_ Vancouver	0	0
Montreal _ Toronto	0	0

Montreal _ LA	20	0.2
Montreal _ Houston	20	0.2

Table 39 Tariff rates from the international plants to the distribution centers

Origin _ Destination	**Tariff rate**
Monterrey_ Vancouver	0.4
Monterrey _ Toronto	0.4
Monterrey _ LA	0.3
Monterrey _ Houston	0.3
Mexico city _ Vancouver	0.4
Mexico city _ Toronto	0.4
Mexico city _ LA	0.3
Mexico city _ Houston	0.3
Guadalajara_ Vancouver	0.4
Guadalajara _ Toronto	0.4
Guadalajara _ LA	0.3
Guadalajara _ Houston	0.3

Table 40 Transportation costs from domestic plants to distribution centers and lead-times

Origin _ Destination	**Transportation cost / Rail**	**Lead-time / Rail**	**Transportation cost/ Truck**	**Lead-time / Truck**
Toronto _ Vancouver	30.75	6	48.45	3
Toronto _ Toronto	1	0	2	0
Toronto _ LA	28.2	10	73.62	5
Toronto _ Houston	16.2	6	24.82	2
Calgary _ Vancouver	6.13	2	8.95	1
Calgary _ Toronto	30.75	6	25.25	2
Calgary _ LA	N/A	N/A	25.17	2

Calgary _ Houston	N/A	N/A	32.49	2
Montreal_ Vancouver	32.75	7	51.45	3
Montreal _ Toronto	2	1	3	0
Montreal _ LA	30.2	11	76.62	5
Montreal _ Houston	N/A	N/A	29.85	2

Table 41 Transportation costs from international plants to distribution centers and lead-times

Origin _ Destination	**Transportation cost / Rail**	**Lead-time / Rail**	**Transportation cost/ Truck**	**Lead-time / Truck**	**Transportation cost/ other**	**Lead-time / other**
Monterrey_ Vancouver	36.25	7	44.55	6	45.57	5
Monterrey _ Toronto	21.94	5.5	25.65	4	N/A	N/A
Monterrey _ LA	N/A	N/A	28.47	2	N/A	N/A
Monterrey _ Houston	N/A	N/A	22.81	2	N/A	N/A
Mexico city _ Vancouver	43.55	8	43.56	8	52.89	6
Mexico city _ Toronto	33.76	6	37.47	4	N/A	N/A
Mexico city _ LA	N/A	N/A	41.65	3	N/A	N/A
Mexico city _ Houston	N/A	N/A	10.99	2	N/A	N/A
Guadalajara_ Vancouver	36.23	8	44.55	7	45.57	5
Guadalajara _	40.21	8	41	6.5	44.71	5

Toronto						
Guadalajara _ LA	N/A	N/A	33.63	2	N/A	N/A
Guadalajara _ Houston	N/A	N/A	30.55	2	N/A	N/A

Table 42 Transportation costs from distribution centers to customer zones and lead-times

Origin	**Transportation cost / Rail**	**Lead -time / Rail**	**Transportation cost/ Truck**	**Lead-time / Truck**
Vancouver _ Toronto	30.75	6	48.45	3
Vancouver _ Halifax	46.125	9	42.675	5
Vancouver _ Seattle	N/A	0	2.86	0
Vancouver _ Chicago	36	8	57.3	4
Vancouver_ LA	N/A	N/A	22.2	2
Toronto _ Toronto	1	N/A	2	0
Toronto _ Halifax	10.25	4	16.15	1
Toronto _ Seattle	30.75	1	48.45	2
Toronto _ Chicago	N/A	2	11.81	1
Toronto _ LA	28.2	10	73.62	5
LA _	28.2	10	73.62	5

Toronto				
LA _ Halifax	38.45	14	89.77	6
LA _ Seattle	N/A	N/A	19.34	1
LA _ Chicago	23.06	8	64.77	5
LA _ LA	1	0	2	0
Houston _ Toronto	N/A	N/A	24.82	2
Houston _ Halifax	N/A	N/A	40.97	3
Houston _ Seattle	17.89	6	35.06	2
Houston _ Chicago	11.06	3	N/A	N/A
Houston _ LA	N/A	N/A	20.34	1

Table 43 Exchange rate of Canada to Mexico in each planning period

Period	**T=1**	**T=2**	**T=3**	**T=4**	**T=5**	**T=6**	**T=7**	**T=8**	**T=9**	**T=10**	**T=11**	**T=12**
Exchange rate	9.39	9.51	9.67	9.88	9.88	10.17	10.20	10.04	9.31	9.39	9.51	9.88

APPENDIX D : Results for Case 3

Table 44 Results for case 3

Decision variables	**T=1**	**T=2**	**T=3**	**T=4**	**T=5**	**T=6**	**T=7**	**T=8**	**T=9**	**T=10**	**T=11**	**T=12**
$Qj_{plant1,t}$	637	531				629						
$Qj_{plant2,t}$		322							322			
$Qj_{plant3,t}$			434									
$QjI_{Iplant1,t}$	221	627										
$QjI_{Iplant2,t}$	214	336	200	588	522							
$QjI_{Iplant3,t}$								307				
$Qjk_{plant1,Dcenter2,r1,t}$	637	431	100			529		100				
$Qjk_{plant2,Dcenter1,r1,t}$	114	100							114	100		
$Qjk_{plant2,Dcenter1,r2,t}$	108								108			
$Qjk_{plant3,Dcenter2,r1,t}$			214									
$Qjk_{plant3,Dcenter2,r2,t}$			220									
$QjIk_{Iplant1,Dcenter2,r1,t}$		319	21			79						
$QjIk_{Iplant1,Dcenter2,r2,t}$	113											
$QjIk_{Iplant1,Dcenter3,r2,t}$	108	208										
$QjIk_{Iplant2,Dcenter4,r2,t}$	214	336	200	488	100	422	100					
$QjIk_{Iplant3,Dcenter3,r2,t}$								207	100			
$Qkl_{Dcenter1,Czone3,r2,t}$			108	108	106					108	108	106
$Qkl_{Dcenter2,Czone1,r2,t}$	109	109	108	108	108	109	108	39	21		54	80
$Qkl_{Dcenter2,Czone2,r1,t}$	107	107			106	107	106	61				

$Qkl_{Dcenter2,Czone2,r2,t}$	107	107	106			107	106				44	
$Qkl_{Dcenter2,Czone3,r1,t}$	106					106						
$Qkl_{Dcenter2,Czone4,r2,t}$	108	108	107	107								
$Qkl_{Dcenter3,Czone5,r1,t}$			108	108				100		107	107	93
$Qkl_{Dcenter4,Czone1,r2,t}$						67	85	107	52	26		
$Qkl_{Dcenter4,Czone3,r1,t}$			106									
$Qkl_{Dcenter4,Czone3,r2,t}$				106		106						
$Qkl_{Dcenter4,Czone4,r1,t}$			108	108	108	108	108	108	108	108	108	
$Qkl_{Dcenter4,Czone5,r2,t}$				107	107	107	7	107			14	

APPENDIX E : Input parameters for the discrete case

Table 45 Demand scenarios for the discrete case

Customer zone	**Low realization**		**Medium realization**		**High realization**	
Toronto	150	25%	160	50%	170	25%
Halifax	100	25%	120	50%	135	25%
Seattle	250	25%	270	50%	300	25%
Chicago	300	30%	325	40%	350	30%
LA	600	30%	700	40%	800	30%

APPENDIX F : Results for Case 7

Table 46 Results for case 7

Decision variables	**T=1**	**T=2**	**T=3**	**T=4**	**T=5**	**T=6**	**T=7**	**T=8**	**T=9**	**T=10**	**T=11**	**T=12**
$Qj_{plant1,t}$	1510	1460	655	960								
$Qj_{plant2,t}$	1670	965		1995								
$Qj_{plant3,t}$	100											
$QjI_{Iplant1,t}$			2670	2920								
$QjI_{Iplant2,t}$			820									
$QjI_{Iplant3,t}$				1295								
$Qjk_{plant1,Dcenter2,r1,t}$	1425	1460	655	860	100							
$Qjk_{plant1,Dcenter4,r2,t}$	85											
$Qjk_{plant2,Dcenter1,r1,t}$		595		1070	100							
$Qjk_{plant2,Dcenter1,r2,t}$	970	270		330								
$Qjk_{plant2,Dcenter2,r2,t}$			100	495								
$Qjk_{plant2,Dcenter3,r2,t}$	700											
$Qjk_{plant3,Dcenter2,r1,t}$				100								
$QjIk_{Iplant1,Dcenter2,r1,t}$	1425	1460	655	860	100							
$QjIk_{Iplant1,Dcenter4,r2,t}$	85											
$QjIk_{Iplant2,Dcenter1,r1,t}$		595		1070	100							
$QjIk_{Iplant2,Dcenter1,r2,t}$	970	270		330								
$QjIk_{Iplant2,Dcenter2,r2,t}$			100	495								
$QjIk_{Iplant2,Dcenter3,r2,t}$	700											
$QjIk_{Iplant3,Dcenter2,r1,t}$				100								

$Qkl_{Dcenter1,Czone1,r1,t}$					60							
$Qkl_{Dcenter1,Czone3,r2,t}$		270	270	270	270	27		270	270	270		270
$Qkl_{Dcenter1,Czone4,r1,t}$				325								
$Qkl_{Dcenter1,Czone5,r2,t}$		700				700	200	700				
$Qkl_{Dcenter2,Czone1,r2,t}$	170	170	170	170	160	170	170	170	170	170	100	160
$Qkl_{Dcenter2,Czone2,r1,t}$		130	130	130			130	130				
$Qkl_{Dcenter2,Czone2,r2,t}$	130	130	130	130			130	130				
$Qkl_{Dcenter2,Czone4,r2,t}$	325	329	325	329	240	325			320	325		
$Qkl_{Dcenter2,Czone5,r1,t}$	700	700										
$Qkl_{Dcenter3,Czone3,r2,t}$						270						
$Qkl_{Dcenter3,Czone5,r1,t}$			700		700	700			300			
$Qkl_{Dcenter4,Czone3,r1,t}$					270							
$Qkl_{Dcenter4,Czone4,r1,t}$			85		350	325						
$Qkl_{Dcenter4,Czone5,r2,t}$						700		200				

APPENDIX G: GAMS results for case 15

```
GAMS                    Rev                 148                              x86_64/Linux
08/23/07 20:56:48 Page 196
General Algebraic Modeling System
Execution

----    391 VARIABLE Qj.L  Quantity of products produced at plant j during t

                t1          t2          t3          t4          t8

plant1    1188.445                                          210.735
plant2     582.875
plant3     100.000     100.000     237.043     100.000


----    391 VARIABLE QjI.L  Quantity of products produced at international plant jI during t

                 t1          t2          t5

Iplant1                 186.618      17.824
Iplant3     149.592


----    391 VARIABLE Qjk.L  Quantity of products shipped from plant j to distribution center k during
t

INDEX 1 = plant1

                    t1          t2          t8          t9

Dcenter1.r1     47.097
Dcenter1.r2    126.677      31.529
Dcenter2.r1    938.872                 148.983      61.752
Dcenter4.r2     44.269

INDEX 1 = plant2

                    t1          t4

Dcenter1.r1    118.296
Dcenter1.r2    249.371      81.124
Dcenter2.r1                 18.876
Dcenter3.r2    115.208

INDEX 1 = plant3

                    t2          t3          t4          t6

Dcenter2.r1    200.000      48.567      99.139       0.861
Dcenter2.r2                188.477


----    391 VARIABLE QjIk.L  Quantity of products shipped from international plant jI to distribution
center k during t
```

```
INDEX 1 = Iplant1

                    t2          t3          t5

Dcenter1.r1                                17.824
Dcenter2.r1    147.431
Dcenter3.r2                39.187

INDEX 1 = Iplant3

                    t1          t2          t3

Dcenter1.r1                27.028
Dcenter1.r2                                 0.001
Dcenter1.r3     49.592                     72.970


----    391 VARIABLE Qkl.L  Quantity of products shipped from distribution center k to customer l
during t

INDEX 1 = Dcenter1

                  t2          t3          t4          t5          t6          t7          t8
t10         t12

Czone1.r1                            40.450
Czone1.r2     76.625                 37.845      38.179                               24.361
Czone2.r1                 21.284
GAMS                  Rev                   148                                  x86_64/Linux
08/23/07 20:56:48 Page 197
General Algebraic Modeling System
Execution


        391 VARIABLE Qkl.L  Quantity of products shipped from distribution center k to customer l
during t

INDEX 1 = Dcenter1

                  t2          t3          t4          t5          t6          t7          t8
t10         t12

Czone2.r2     53.378                 36.229
Czone3.r2                                        42.644                 12.153                30.293
17.824
Czone4.r1                  8.826
Czone4.r2     45.358      45.543
Czone5.r2      74.009                                  44.182      49.592      47.097      48.610
27.030

INDEX 1 = Dcenter2

                  t1          t2          t3          t4          t6          t7          t8
t9          t12

Czone1.r2        214.898                                  92.364          80.345          72.271
60.409      18.876
Czone2.r1     91.466      15.006                                          38.552
Czone2.r2      215.028                      92.170                                      55.661
42.114
```

```
Czone3.r1    115.855               21.064                16.668                22.751
20.898
Czone3.r2                                                                      10.201
11.549
Czone4.r2    117.996     84.994    82.879     68.221               54.079      26.233
26.782
Czone5.r1     34.015
Czone5.r2     49.615

INDEX 1 = Dcenter3

                t3          t5

Czone3.r2                  39.187
Czone5.r1    115.208

INDEX 1 = Dcenter4

                t4

Czone5.r2     44.269


----    391 VARIABLE Ij.L              Inventory level at domestic plants

                t1          t2          t3          t4          t5          t8

plant1       31.529                                                        61.752
plant2      100.000     100.000     100.000
plant3      100.000                              0.861       0.861


----    391 VARIABLE IjI.L             Inventory level at international plants

                t1          t2

Iplant1                  39.187
Iplant3     100.000      72.972


----    391 VARIABLE Ik.L              Inventory level at distribution centres

                t1          t3          t5          t8         t10         t11

Dcenter2    100.000     100.000      99.139     100.000      18.876      18.876
Dcenter4                 44.269


----    391 VARIABLE SL3.L             Expected sales

                t1          t2          t3          t4          t5          t6          t7          t8
t9

Czone1      100.000     103.399     103.398     103.384     103.399     103.222     103.273
103.399     103.252
Czone2                  100.000     103.399     103.398     102.319     103.391     103.388
103.239     103.393
Czone3                  103.392     103.342     103.329     103.378     103.320     103.282
103.365     103.349
Czone4                  103.313     103.394     103.394     103.327     103.343     103.393
```

```
103.383    103.375
Czone5                          103.399    103.060    103.360    103.320    103.363
103.346    103.356
GAMS              Rev              148                                x86_64/Linux
08/23/07 20:56:48 Page 198
General Algebraic Modeling System
Execution

      391 VARIABLE SL3.L

    +       t10        t11        t12

Czone1     103.247    103.240    103.393
Czone2     103.370    103.265    103.394
Czone3     103.291    103.353    103.397
Czone4     103.246    103.210    103.394
Czone5     103.347    103.319    103.396


----    391 VARIABLE sumqlt.L           Total amount received at customer zones at each period

              t1         t2         t3         t4         t5         t6         t7         t8
t9

Czone1     214.898                92.364     80.345     76.625     72.271     37.845
38.179     60.409
Czone2                215.028                92.170     91.466     15.006     53.378
55.661     36.229
Czone3                115.855     42.644     33.218     30.293     39.187     16.668
10.201     22.751
Czone4                117.996     84.994     82.879     68.221     45.358     45.543
54.079     26.233
Czone5                           115.208     74.009     44.269     49.615     44.182
49.592     47.097

    +       t10        t11        t12

Czone1      40.450     24.361     18.876
Czone2      42.114     38.552     21.284
Czone3      20.898     11.549     17.824
Czone4      26.782      8.826
Czone5      48.610     34.015     27.030


----    391 VARIABLE overstock.L

              t1         t2         t3         t4         t5         t6         t7         t8
t9

Czone1     114.898     11.499     11.963     12.851     11.778     16.163     15.387
11.712     15.719
Czone2                115.028     11.628     12.028     25.232     12.542     12.700
15.920     12.438
Czone3                 12.463     14.080     14.366     13.114     14.550     15.238
13.503     13.926
Czone4                 14.683     10.964     12.379     14.409     14.058     12.442
12.904     13.183
Czone5                            11.809     18.185     13.650     14.547     13.551
14.001     13.743
```

```
    +        t10         t11         t12

Czone1      15.797      15.902      10.893
Czone2      13.371      15.514      10.975
Czone3      15.089      13.821      11.176
Czone4      15.817      16.335      10.953
Czone5      13.979      14.569      11.049
GAMS                    Rev                    148                                x86_64/Linux
08/23/07 20:56:48 Page 199
General Algebraic Modeling System
Execution

----     391 VARIABLE LostSale.L

                 t1          t2          t3          t4          t5          t6          t7          t8
t9

Czone1 2.783938E-8       2.788       2.681       2.489       2.723       1.883       2.011
2.738        1.955
Czone2     100.000 2.679097E-8       2.757       2.666       0.842       2.554       2.520
1.922        2.576
Czone3     100.000       2.571       2.245       2.191       2.434       2.157       2.036
2.356        2.274
Czone4     100.000       2.134       2.916       2.589       2.183       2.249       2.575
2.478        2.420
Czone5     100.000     100.000       2.716       1.584       2.327       2.158       2.347
2.260        2.309

    +        t10         t11         t12

Czone1       1.942       1.925       2.933
Czone2       2.382       1.989       2.913
Czone3       2.062       2.294       2.864
Czone4       1.939       1.855       2.918
Czone5       2.264       2.154       2.895


----     391 VARIABLE totallost.L       =    62394.031  total lost sale
             VARIABLE totaloverstock.L    =    48023.710  total overstock
             VARIABLE SumP.L              =    26561.652  total production costs
             VARIABLE SumT.L              =   112285.148  total transportation costs
             VARIABLE SumI.L              =     4431.254  total inventory costs
             VARIABLE SumCap.L            =    38817.299  total capacity expansion costs
             VARIABLE Tprice.L            =    22964.759  total transfer cost
             VARIABLE TTariff.L           =     2072.126  total tariff cost
             VARIABLE z.L                 =   317549.979  Stochastic objective function
             VARIABLE ASL.L               =        0.946  expected average service level
             VARIABLE SumQj.L             =     2519.099  total domestic production amount
             VARIABLE SumQjI.L            =      354.034  total international production amount
             VARIABLE sumsales.L          =     5676.000  total expected sales


EXECUTION TIME       =        0.030 SECONDS      3 Mb   LEX225-148 May 29, 2007


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```

APPENDIX H: GAMS results for case 16

```
GAMS                  Rev                   148                                x86_64/Linux
08/23/07 21:00:01 Page 5332
General Algebraic Modeling System
Execution
----    408 VARIABLE Qj.L  Quantity of products produced at plant j during t

              t1          t2          t3          t4          t6          t7          t9

plant1    1290.000                 945.000                             1215.000
plant2     270.000    1040.000                                                     2625.000
plant3                                         645.000     485.000


----    408 VARIABLE QjI.L  Quantity of products produced at international plant jI during t

              t1          t4

Iplant1   3251.227    2405.000
Iplant2               1850.000


----    408 VARIABLE Qjk.L  Quantity of products shipped from plant j to distribution center k during
t

INDEX 1 = plant1

                  t1          t2          t3          t4          t7         t10         t12

Dcenter2.r1   1190.000     100.000     845.000     100.000    1115.000      30.000      70.000

INDEX 1 = plant2

                  t1          t2          t3          t9         t10

Dcenter1.r1                370.000     100.000     370.000     100.000
Dcenter1.r2    270.000     570.000                 970.000
Dcenter2.r2                                        485.000
Dcenter3.r2                                        700.000

INDEX 1 = plant3

                  t4          t6

Dcenter2.r1    190.000
Dcenter2.r2    455.000     485.000


----    408 VARIABLE QjIk.L  Quantity of products shipped from international plant jI to distribution
center k during t

INDEX 1 = Iplant1

                  t1          t3          t4          t7

Dcenter1.r1    656.227
Dcenter1.r2    200.000
Dcenter1.r3    570.000                 270.000
Dcenter2.r1                            645.000
```

```
Dcenter2.r2                          320.000
Dcenter3.r2    800.000      100.000    1070.000      100.000
Dcenter4.r2    925.000

INDEX 1 = Iplant2

                   t4           t6

Dcenter2.r1     455.000
Dcenter4.r2    1295.000      100.000


----    408 VARIABLE Qkl.L  Quantity of products shipped from distribution center k to customer l
during t

INDEX 1 = Dcenter1

                  t2            t3            t4            t5            t6            t7            t8
t9           t10

Czone3.r2          270.000            270.000            270.000            200.000            270.000
270.000      270.000
Czone5.r2                   300.000                                     300.000      200.000      656.227
700.000
GAMS                  Rev                   148                                    x86_64/Linux
08/23/07 21:00:01 Page 5333
General Algebraic Modeling System
Execution

       408 VARIABLE Qkl.L  Quantity of products shipped from distribution center k to customer l
during t

INDEX 1 = Dcenter1

       +        t11          t12

Czone3.r2    270.000      200.000

INDEX 1 = Dcenter2

                  t1            t2            t3            t4            t5            t6            t7
t8           t9

Czone1.r2     170.000      150.000      160.000      160.000      160.000      160.000      160.000
160.000     160.000
Czone2.r1     130.000                   130.000                                                130.000
130.000
Czone2.r2     203.333       36.667      130.000                   130.000                      130.000
130.000      60.000
Czone3.r1                                      70.000                          270.000
Czone4.r2     586.667       13.333      325.000      325.000                   325.000      325.000
325.000

       +        t10          t11          t12

Czone1.r2     160.000      160.000      170.000
Czone4.r2     325.000      325.000

INDEX 1 = Dcenter3
```

```
                t3          t5          t6          t9         t11

Czone3.r2                            270.000
Czone5.r1     700.000     200.000     700.000     200.000     700.000

INDEX 1 = Dcenter4

                t3          t4          t6          t8

Czone3.r1                             70.000
Czone4.r1     325.000                 325.000
Czone5.r2     500.000     100.000     800.000     200.000


----    408 VARIABLE Ij.L     Inventory level at domestic plants

              t1          t2          t3          t7          t8          t9         t10         t11

plant1     100.000                 100.000     100.000     100.000     100.000      70.000
70.000
plant2                 100.000                                         100.000


----    408 VARIABLE IjI.L    Inventory level at international plants

               t1          t2          t4          t5          t6

Iplant1     100.000     100.000     100.000     100.000     100.000
Iplant2                           100.000     100.000


----    408 VARIABLE Ik.L     Inventory level at distribution centers

                t1          t3          t4          t6          t7          t8          t9
t10         t11

Dcenter1                                                                             100.000
100.000
Dcenter2     100.000     100.000     100.000                 100.000                 100.000
100.000     100.000
Dcenter3                 100.000     100.000     100.000     100.000     100.000
Dcenter4                 100.000                 100.000     100.000


----    408 VARIABLE sumqlt.L     Total amount received at customer zones in each period

              t1          t2          t3          t4          t5          t6          t7          t8
t9

Czone1     170.000     150.000     160.000     160.000     160.000     160.000     160.000
160.000     160.000
Czone2                 203.333      36.667     130.000     130.000     130.000     130.000
130.000     130.000
Czone3                 270.000     270.000     270.000     270.000     270.000     270.000
270.000     270.000
Czone4                 586.667      13.333     325.000     325.000     325.000     325.000
325.000     325.000
```

```
GAMS                    Rev                  148                              x86_64/Linux
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General Algebraic Modeling System
Execution


          408 VARIABLE sumqlt.L

                t1         t2         t3         t4         t5         t6         t7         t8
t9

Czone5                                700.000    500.000    600.000    700.000    800.000
300.000     600.000

    +           t10        t11        t12

Czone1      160.000     160.000    170.000
Czone2       60.000     130.000    130.000
Czone3      270.000     270.000    270.000
Czone4      325.000     325.000    325.000
Czone5      656.227     700.000    700.000


----     408 VARIABLE Sumsales.L        Expected sales

                t1         t2         t3         t4         t5         t6         t7         t8
t9

Czone1      160.000     155.000    157.500    157.500    157.500    157.500    157.500
157.500     157.500
Czone2                  117.500    112.500    117.500    117.500    117.500    117.500
117.500     117.500
Czone3                  265.000    265.000    265.000    265.000    265.000    265.000
265.000     265.000
Czone4                  325.000    275.000    317.500    317.500    317.500    317.500
317.500     317.500
Czone5                             670.000    530.000    600.000    670.000    700.000
430.000     600.000

    +           t10        t11        t12

Czone1      157.500     157.500    160.000
Czone2      100.000     117.500    117.500
Czone3      265.000     265.000    265.000
Czone4      317.500     317.500    317.500
Czone5      639.359     670.000    670.000


----     408 VARIABLE Sumback.L         Lostsale   amount

                t1         t2         t3         t4         t5         t6         t7         t8
t9

Czone1                    5.000      2.500      2.500      2.500      2.500      2.500
2.500       2.500
Czone2      117.500                5.000
Czone3       272.500      7.500      7.500      7.500      7.500      7.500      7.500
7.500       7.500
Czone4       325.000                50.000      7.500      7.500      7.500      7.500
7.500       7.500
```

```
Czone5      700.000      700.000        30.000       170.000      100.000        30.000
270.000    100.000

    +        t10         t11         t12

Czone1      2.500       2.500
Czone2     17.500
Czone3      7.500       7.500       7.500
Czone4      7.500       7.500       7.500
Czone5     60.641      30.000      30.000


----     408 VARIABLE Sumover.L          Overstock amount

              t1          t2          t3          t4          t5          t6          t7          t8
t9

Czone1      10.000       5.000       7.500      10.000      12.500      15.000      17.500
20.000     22.500
Czone2                  85.833      10.000      22.500      35.000      47.500      60.000
72.500     85.000
Czone3                   5.000      10.000      15.000      20.000      25.000      30.000
35.000     40.000
Czone4                 261.667                   7.500      15.000      22.500      30.000
37.500     45.000
Czone5                          30.000                              30.000     130.000

    +        t10         t11         t12

Czone1     25.000      27.500      37.500
Czone2     45.000      57.500      70.000
Czone3     45.000      50.000      55.000
GAMS                 Rev               148                                  x86_64/Linux
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General Algebraic Modeling System
Execution

       408 VARIABLE Sumover.L

    +        t10         t11         t12

Czone4     52.500      60.000      67.500
Czone5     16.868      46.868      76.868

----     408 VARIABLE lostcost.L              =  318564.142   total lost sale cost
             VARIABLE overcost.L              =   103030.195   total overstock cost
             VARIABLE SumP.L                  =    64574.212   total production cost
             VARIABLE SumT.L                  =   573281.858   total transportation cost
             VARIABLE SumI.L                  =     8853.747   total inventory cost
             VARIABLE SumCap.L                =   173851.035 total capacity expansion cost
             VARIABLE Tprice.L                =    16800.000   total transfer cost
             VARIABLE TTariff.L               =    17276.813   total tariff cost
             VARIABLE z.L                     =  1276232.003   Stochastic objective function
             VARIABLE ASL.L                   =        0.880   expected average service level

EXECUTION TIME        =         0.610 SECONDS      10 Mb  LEX225-148 May 29, 2007
USER: Guoqing Zhang                              G070507:1625AP-LNX
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```

APPENDIX H: Input parameters for cases 17 and 18

Table 47 Unit transportation cost reduction percentage for shipment from j via r, corresponding to interval m

Domestic plant/Transportation mode	Interval: m1	Interval: m2	Interval: m3
Plant1.r1	0.1	0.15	0.2
Plant1.r2	0.12	0.14	0.21
Plant1.r3	0.15	0.18	0.23
Plant2.r1	0.1	0.15	0.2
Plant2.r2	0.12	0.14	0.21
Plant2.r3	0.15	0.18	0.23
Plant3.r1	0.1	0.15	0.2
Plant3.r2	0.12	0.14	0.21
Plant3.r3	0.15	0.18	0.23

Table 48 Unit transportation cost reduction percentage for shipment from jI via r, corresponding to interval m

International plant/Transportation mode	Interval: m1	Interval: m2	Interval: m3
IPlant1.r1	0.1	0.15	0.2
IPlant1.r2	0.12	0.14	0.21
IPlant1.r3	0.15	0.18	0.23
IPlant2.r1	0.1	0.15	0.2
IPlant2.r2	0.12	0.14	0.21
IPlant2.r3	0.15	0.18	0.23
IPlant3.r1	0.1	0.15	0.2
IPlant3.r2	0.12	0.14	0.21

IPlant3.r3	0.15	0.18	0.23

Table 49 Unit transportation cost reduction percentage for shipment from k via r, corresponding to interval m

International plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
Dcenter1.r1	0.1	0.15	0.2
Dcenter1.r2	0.12	0.14	0.21
Dcenter1.r3	0.15	0.18	0.23
Dcenter2.r1	0.1	0.15	0.2
Dcenter2.r2	0.12	0.14	0.21
Dcenter2.r3	0.15	0.18	0.23
Dcenter3.r1	0.1	0.15	0.2
Dcenter3.r2	0.12	0.14	0.21
Dcenter3.r3	0.15	0.18	0.23
Dcenter4.r1	0.1	0.15	0.2
Dcenter4.r2	0.12	0.14	0.21
Dcenter4.r3	0.15	0.18	0.23

Table 50 Upper bound on shipment quantity from j via r, corresponding to interval m

Domestic plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
Plant1.r1	150	250	5000
Plant1.r2	100	200	5000
Plant1.r3	80	180	5000
Plant2.r1	150	250	5000
Plant2.r2	100	200	5000

Plant2.r3	80	180	5000
Plant3.r1	150	250	5000
Plant3.r2	100	200	5000
Plant3.r3	80	180	5000

Table 51 Upper bound on shipment quantity from jI via r, corresponding to interval m

International plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
IPlant1.r1	150	250	5000
IPlant1.r2	100	200	5000
IPlant1.r3	80	180	5000
IPlant2.r1	150	250	5000
IPlant2.r2	100	200	5000
IPlant2.r3	80	180	5000
IPlant3.r1	150	250	5000
IPlant3.r2	100	200	5000
IPlant3.r3	80	180	5000

Table 52 Upper bound on shipment quantity from k via r, corresponding to interval m

International plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
Dcenter1.r1	150	250	5000
Dcenter1.r2	100	200	5000
Dcenter1.r3	80	180	5000
Dcenter2.r1	150	250	5000
Dcenter2.r2	100	200	5000
Dcenter2.r3	80	180	5000
Dcenter3.r1	150	250	5000
Dcenter3.r2	100	200	5000

Dcenter3.r3	80	180	5000
Dcenter4.r1	150	250	5000
Dcenter4.r2	100	200	5000
Dcenter4.r3	80	180	5000

Table 53 Lower bound on shipment quantity from j via r, corresponding to interval m

Domestic plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
Plant1.r1	0	150	250
Plant1.r2	0	100	200
Plant1.r3	0	80	180
Plant2.r1	0	150	250
Plant2.r2	0	100	200
Plant2.r3	0	80	180
Plant3.r1	0	150	250
Plant3.r2	0	100	200
Plant3.r3	0	80	180

Table 54 Lower bound on shipment quantity from jI via r, corresponding to interval m

International plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
IPlant1.r1	0	150	250
IPlant1.r2	0	100	200
IPlant1.r3	0	80	180
IPlant2.r1	0	150	250
IPlant2.r2	0	100	200
IPlant2.r3	0	80	180
IPlant3.r1	0	150	250
IPlant3.r2	0	100	200

IPlant3.r3	0	80	180

Table 55 Lower bound on shipment quantity from k via r, corresponding to interval m

International plant/Transportation mode	**Interval: m1**	**Interval: m2**	**Interval: m3**
Dcenter1.r1	0	150	250
Dcenter1.r2	0	100	200
Dcenter1.r3	0	80	180
Dcenter2.r1	0	150	250
Dcenter2.r2	0	100	200
Dcenter2.r3	0	80	180
Dcenter3.r1	0	150	250
Dcenter3.r2	0	100	200
Dcenter3.r3	0	80	180
Dcenter4.r1	0	150	250
Dcenter4.r2	0	100	200
Dcenter4.r3	0	80	180

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