Capacities-based supply chain network design considering demand uncertainty using two-stage stochastic programming

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Abstract The design of a supply chain (SC) aims to minimize cost so the product can reach the customer at the cheapest cost with flexible demand. The demand of a product is variable with time and environment. Most of the researchers have considered investment cost, processing cost, and transportation cost as variable costs to minimize the cost while considering a constant demand. In actual practice, the demands are flexible. In this paper, a two-stage stochastic programming model has been proposed for a capacities-based network design of a supply chain for flexible demands while considering inventory carrying cost and missed opportunity cost in addition to the above-mentioned costs. It will enhance the logistic planning and seek the location network optimally. Furthermore, in the first stage, decision variables represent different nodes (facility locations of echelons) of the supply chain, with the assumption that they will be considered at the design stage before uncertain parameters are unveiled. On the other hand, decision variables related to the amount of products to be produced and stored in the nodes of the SC, the flows of materials among the entities of the network, and shortfalls and excess at the customer centers are considered as second-stage variables. The methodology has been illustrated by solving an example. It was found that the proposed model yields more feasible and advantageous results.

Keywords Supply chain network design · Facility locations · Inventories

1 Introduction

The efficient design and operation of a supply chain (SC) has been a matter of concern for researchers for the planning activities of a manufacturing firm. Supply chain network design decisions include the assignment of facility role, location of manufacturing, storage, transportation-related facilities, and allocation of capacities and market to each facility [4]. SC planning is categorized as strategic-level SC planning and tactical-level SC planning. Strategic-level SC planning decides the configuration of the network, i.e., the number, location, capacity, and technology of the facilities, whereas tactical-level planning of SC operations includes the decision of aggregate quantities and material flows for purchasing, processing, and distributing. The strategic configuration of the SC is considered to be a key factor that affects the efficient tactical operations and consequently has a long-lasting impact on the firm. Furthermore, the fact that the SC configuration involves the commitment of substantial capital resources over a long period of time makes the SC design problem an intricate and important one.

For the long term, SC planning while considering factors makes the problem too complex while using mathematical programming alone and may require scenario planning [27, 29]. The solution of models has been attempted in three ways: using multiple-stage solutions of deterministic models [5, 9], through simulation of deterministic models [12], and through stochastic programming [1, 8]. A real SC design problem comprises numerous sources of technical and commercial uncertainty. However, most of the researchers have considered deterministic governing parameters, such as cost coefficients, supplies, and demand [12, 27].

Some of the researchers have addressed comprehensive (strategic and tactical issues simultaneously) design of SC networks using two-stage stochastic models. MirHassani et al. [19] have considered a two-stage model for multi-period capacity planning of SC networks. They have used benders

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decomposition to solve the resulting stochastic integer program. Tsiakas et al. [30] have also considered a two-stage stochastic programming model for SC network design under demand uncertainty. They have developed a large-scale mixed-integer linear programming model for this problem. Alonso-Ayuso et al. [1] proposed a branch-and-fix heuristic for solving two-stage stochastic SC design problems. Santoso et al. [23] integrated a sampling strategy with an accelerated Benders decomposition to solve SC design problems with accomplishing uncertain parameters using probabilistic continuous distribution. Gupta and Maranas [10], Gupta et al. [11], and Petkov and Maranas [20] have considered the uncertainty of demands as multivariate-normal distributions. Then, they have converted stochastic features of the problem into a chance-constraint programming problem.

Many supply chain network design models are available in the literature [6, 24, 26]. They vary in the ingredients which form the model. They may consider only strategic locating cost in their modeling or also consider operational transportation and inventory holding cost in their design modeling. Furthermore, failure to take the related extra inventory and shortage costs into consideration when deciding the locations of facilities in the supply chains’ networks can lead to sub-optimality. We refer the reader to Shen [25] for a review of supply chain network design literature. Some of the design models proposed are stochastic reformulations of classical location–allocation models, and others extend the location–transportation model proposed by Klibi et al. [15] to take into account depot capacity, disruptions, and resilience strategies. These models are solved using the sample average approximation method, as is commonly done in stochastic programming.

Most of the supply chain network design problems can be reduced to capacitated facility location problem which is known to be NP-complete; therefore, most of the supply chain network design problems are NP-hard. To cope with the complexity of supply chain network design problems, many heuristic algorithms [3, 13, 31] and metaheuristics such as genetic algorithm [2, 18], simulated annealing [14, 22], tabu search [16, 28], memetic algorithm [21], and scatter search [7] are developed and used by authors in the recent decade. The need for more efficient solution approaches overcoming more complex network design models has recently been emphasized by Melo et al. [17] in their comprehensive review article.

In this paper, the effects of the parameter of uncertain characteristic in production system have been analyzed. A two-stage stochastic model is proposed for the effective design of the supply chain network. The model considers understocking and overstocking for which a penalty and excess cost, respectively, is included. In these models, two types of decision variables have been considered. The first-stage variables are concerned with the existence, location, and capacities of the plant. These variables are corresponding to those decisions that are deterministic in nature. The second-stage variables accommodated the uncertainty of parameters or time-dependent parameters. With the help of these parameters, decision makers take the decisions of the location and capacity of the plants or warehouses and numbers of the products between supply chain echelons.

The paper has been organized as follows: In Section 2, a linear programming model has been proposed. Section 3 describes the development of the two-stage stochastic model. A numerical example has been considered in Section 4. This example has been solved by a deterministic model proposed by [23] and by a proposed two-stage stochastic model. Finally, the conclusions have been drawn in Section 5.

2 Extended linear programming model

In this section, a mathematical model for the design of a supply chain network has been proposed. The model is subjected to various risks involved at different levels of the supply network. The objective of the proposed model is to evaluate optimal locations of echelons and to determine the quantities flow between them to minimize overall cost. The parameters and the decision variables used to formulate the model are listed in Table 1.

Consider a deterministic supply chain network \(G=(N, A)\), where \(N\) is the set of nodes and \(A\) is the set of arcs. The set \(N\) consists of the set of suppliers \(S\), the set of possible processing facilities \(P\), and the set of customer centers \(C\), i.e., \(N=S\cup P\cup C\). The processing facilities include manufacturing centers \(M\) and warehouses \(W\), i.e., \(P=M\cup W\). Let \(K\) be the set of products flowing through the supply chain [23].

The SC configuration decisions consist of the selection of processing centers to be considered. A binary variable is associated with these centers in such a way that \(y_i=1\) if the processing facility is considered; otherwise, \(y_i=0\). The tactical decisions consist of routing the flow of each product \(k\in K\) from the suppliers to the customers. Let \(x_{ij}^k\) denote the flow of product \(k\) from a node \(i\) to a node \(j\) of the network where \((ij)\in A\), \(z_{ij}^k\) denotes shortfall of product \(k\) at customer center \(j\), and \(z_{ij}^k\) denotes an excess of product \(k\) at customer center \(j\). A deterministic mathematical model for this SC design problem is formulated as:

\[
\min \sum_{ij\in A} c_{ij}y_i + \sum_{k\in K} \sum_{(ij)\in A} q_{ij}x_{ij}^k + \sum_{k\in K} \sum_{j\in C} b_j z_{ij}^k + \sum_{k\in K} \sum_{j\in C} g_j z_{ij}^k \quad (1.1)
\]

s.t. \(y\in Y\subset\{0,1\}^{\vert P\vert}\)  

(1.2)