Omega 40 (2012) 511–524

Contents lists available at SciVerse ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

A multi-stage stochastic supply network design problem with financial decisions and risk management

Stefan Nickel [a,b], Francisco Saldanha-da-Gama [c], Hans-Peter Ziegler [a,*]

[a] Institute for Operations Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[b] Fraunhofer Institute for Industrial Mathematics (ITWM), Kaiserslautern, Germany
[c] DEIO-CIO, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

ARTICLE INFO

Article history:
Received 10 May 2010
Accepted 24 September 2011
Processed by B. Lev
Available online 17 October 2011

Keywords:
Stochastic programming
Location
Integer programming

ABSTRACT

In this paper, a multi-period supply chain network design problem is addressed. Several aspects of practical relevance are considered such as those related with the financial decisions that must be accounted for by a company managing a supply chain. The decisions to be made comprise the location of the facilities, the flow of commodities and the investments to make in alternative activities to those directly related with the supply chain design. Uncertainty is assumed for demand and interest rates, which is described by a set of scenarios. Therefore, for the entire planning horizon, a tree of scenarios is built. A target is set for the return on investment and the risk of falling below it is measured and accounted for. The service level is also measured and included in the objective function. The problem is formulated as a multi-stage stochastic mixed-integer linear programming problem. The goal is to maximize the total financial benefit. An alternative formulation which is based upon the paths in the scenario tree is also proposed. A methodology for measuring the value of the stochastic solution in this problem is discussed. Computational tests using randomly generated data are presented showing that the stochastic approach is worth considering in these types of problems.

1. Introduction

Structuring a global supply chain is a complex decision making process. The complexity arises from the need to integrate several decisions each of which with a relevant contribution to the performance of the whole system. In such problems, the typical input includes a set of markets, a set of products to be manufactured and/or distributed, demand forecasts for the different markets and some information about future conditions (e.g. production and transportation costs). Making use of the above information, companies must decide where facilities (e.g. plants, distribution centers) should be set operating, how to allocate procurement/production activities to the different facilities, and how to plan the transportation of products through the supply chain network in order to satisfy customer demands. Often, the objective considered is the minimization of the costs for building and operating the network.

Historically, researchers have focused relatively early on the design of production/distribution systems (see [10]). Typically, discrete facility location models were proposed which possibly included some additional features but that still had a limited scope and were not able to deal with many realistic supply chain requirements. However, in the last decade, much research has been done to progressively develop more comprehensive (but tractable) models that can better capture the essence of many supply chain network design (SCND) problems and become a useful tool in the decision making process. This can be seen in the papers by Melo et al. [27] and Shapiro [39], where it also becomes clear that many aspects of practical relevance in supply chain management (SCM) are still far from being fully integrated in the models existing in the literature.

As pointed out by Shapiro [39], in corporate planning, financial decisions may strongly interact with the supply chain planning. In fact, structuring and managing a supply chain is often just part of a whole set of activities associated with a company. Accordingly, the investments in the supply chain must be integrated with other profitable investments. Typically, several points in time can be considered, in which the investments can be made or in which their return can occur (which in turn, may allow further investments in the supply chain). Additionally, due to the large capital often associated with the network design decisions, the possibility of taking advantage of some investment opportunity is often considered, which justifies the use of loans.

The evaluation of the investments made in a supply chain is usually based on their return rate. This fact calls for the inclusion of revenues in SCND models, which also gives the possibility of

* Corresponding author. Tel.: +49 721 608 43951.
E-mail address: hans-peter.ziegler@kit.edu (H.-P. Ziegler).

0305-0483/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.omega.2011.09.006

setting a target for the return on investment (ROI). The inclusion of the ROI in SCND models has not received attention in the literature.

In addition to the financial aspects just mentioned, the multi-period nature of some decisions has often to be accommodated in SCND models. Usually, a supply chain network has to be in use for some time during which the underlying conditions may change. In some situations, a single-period facility location model may be enough to find a ''robust'' network design. However, in most cases, it is possible and even desirable to allow a change in the decisions in order to better absorb the changes in the parameters and thus to adjust the system accordingly. Location decisions are often among such decisions. In such cases, typically, there is a discrete set of points in time in which changes can be made in the network structure. These points allow a partition of the planning horizon into several time periods and constitute the initial setting for a multi-period network design problem. As pointed out by Melo et al. [26] the existence of a periodic budget (e.g. annual, quarterly) for investments in the supply chain is also a situation requiring the use of a multi-period modeling framework.

Another feature that can hardly be avoided in many SCND problems regards the uncertainty associated to the future conditions which may influence the input of the problem, and the need to include this uncertainty in the models supporting the decision making process. Different sources of uncertainty exist that can be included in the models (see [40]) such as demand, production or distribution costs, supply of raw materials, etc. The uncertainty existing in these data leads to the need to find robust SCND decisions and/or consider ways for measuring and optimizing the risk associated with those decisions.

A constraint often considered in the literature devoted to SCND problems is that all the demand must be supplied throughout the planning horizon. However, for several reasons such constraint may become meaningless. Firstly, because demand is uncertain. Secondly because due to the existence of other investments in alternative to those that can be made in the supply chain, the company may find it better not to invest in a supply chain the amount needed to assure the complete demand satisfaction. Finally, it may simply be a marketing strategy not to supply all the demand in some time horizon. Taking these arguments into consideration, a more interesting and from a practical point of view more reasonable alternative is to measure the service level (e.g. the proportion of satisfied demand) and to reward it in the objective function.

The contribution of this paper is to provide a new modeling framework for supply network design problems capturing all the above-mentioned features. Accordingly, we consider a multi-period multi-commodity stochastic supply chain network design problem with financial decisions and risk management ($SCND_{MSFR}$). A planning horizon is considered, which is divided into several time periods. In each period several decisions must be made namely, (i) the facilities that should be operating and thus the investments to make in the supply chain structure, (ii) other investments to make in addition to the previous ones, (iii) the loans to get and (iv) the flow of commodities through the network. Stochasticity is taken into account for the demand and for the interest rates. A set of scenarios is considered for describing the uncertainty. Revenues are included in the model as well as the ROI. The service level for each customer is evaluated and weighted in the objective function. Finally, a measure of risk is introduced. The objective is to minimize the overall cost which is evaluated considering the investments made, the revenues, and the transportation costs. The problem is formulated as a mixed-integer multi-stage stochastic programming problem, deriving the deterministic equivalent program. A more simplified and from a computational point of view more attractive formulation, which is based on the paths in the scenario tree, is presented afterwards.

The features that we consider in the new modeling framework have been considered in the literature although, to the best of the authors knowledge, their integration was never attempted. Two of such features which are unavoidable in SCND regard the multi-period, multi-commodity nature of many realistic problems. As it has been noticed by Melo et al. [27] such features have been addressed in the literature but mostly in a deterministic setting. Fleischmann et al. [9] consider a problem in which the decisions to be made regard location, distribution, capacity, production and investment. The objective is to optimize the net present value. In the problem studied by Hugo and Pistikopoulos [20] the decisions involve location, distribution and capacity of the facilities. Two objectives are considered: the net present value (to maximize) and the potential environmental impact (to minimize). Ulstein et al. [42] consider the location of a single echelon of facilities. The decisions also involve the flow of commodities through the network and the capacity of the facilities. A profit maximization objective is considered. Canel et al. [6] consider a SCND problem and search for the best location for a set of intermediate facilities in a two-layer network as well as for the best way for shipping the commodities through the network. Hinojosa et al. [16,17] consider two location layers with location decisions to be made for both layers. In the first paper, location and shipment decisions are considered. The second paper considers, in addition, inventory and procurement decisions. Finally, Melo et al. [26] consider a generic number of echelons with the possibility of making location decisions in all layers. Production, distribution, procurement, capacity and investment decisions are also considered.

The inclusion of uncertainty issues in SCND problems in general and in facility location models in particular is not new and has been addressed by many authors (see [40]). Nevertheless, as pointed out by Melo et al. [27], the scope of the models that have been proposed is still rather limited due to the natural complexity of many stochastic optimization problems. In particular, most of the literature considers single-period single-commodity problems. Nevertheless, several papers can be found addressing multi-commodity problems in a single-period context. This is the case with the problems studied by Guillén et al. [13], Listeş and Dekker [24], Sabri and Beamon [35] and Santoso et al. [36]. These authors consider two to multiple echelons. The decisions concern the flow of commodities, capacities, production or procurement and inventory decisions. Stochasticity is assumed for demand, production costs and delivery costs, respectively and the objectives concern the profit, the net revenue, the costs, the demand satisfaction or just the flexibility (regarding the volume or delivery).

The combination of multi-period decisions with a stochastic setting is proposed by Aghezzaf [1] although considering only a single commodity. Two facility layers are considered with location decisions being made for just one of them. In addition to the location decisions, distribution, inventory and capacity decisions are also considered. Stochasticity is assumed for the demands. A robust optimization approach is proposed for the problem. The same type of approach was also proposed by Pan and Nagi [33] who considered a multiple layer supply chain network. Demand is assumed to be uncertain. Distribution, production and inventory decisions are considered in addition to the decision of where to locate the facilities.

As mentioned above, the possibility of not satisfying all the demand makes sense in many SCND problems. This possibility has been modeled by a few authors. Sabri and Beamon [35] consider the service level as one objective function to maximize in a bi-objective optimization problem. Hwang [21] considers a single-commodity SCND problem with two facility layers. Location as well as routing decisions are considered. Stochasticity is associated with traveling time (assumed to have a known distribution). A minimum service