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An integrated model for strategic supply chain design: Formulation and ABC-based solution approach

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ABSTRACT

This study develops a mixed integer nonlinear programming (MINLP) model to design supply chains. In view of the limitations of many available strategic supply chain design models, this model involves three major supply chain stages, including procurement, production, and distribution, and their interactions; it takes into account bill of materials constraints for modeling complex supply chain inter-relationships. In addition, in accordance with the fact that companies nowadays develop product families, our model addresses multi-product supply chain design to respond to diverse customer requirements. Recognizing their importance, this study identifies and formulates constraints related to facility pairwise relationships and supplier priority along with the classical constraints from the available literature. To efficiently solve such a highly constrained, large scale MINLP model, we develop an approach based on an artificial bee colony (ABC) algorithm. Bicycle design and production is used to demonstrate the potential of the MINLP model for designing supply chains and the performance of the ABC-based solution approach in solving the model. The proposed model and solution approach can be considered as two fundamental components of an expert system in the broad sense. Thus, this study is expected to stimulate more future research on the development of practical expert systems for designing supply chains.

1. Introduction

A supply chain involves multiple facilities (i.e., supply chain members), such as raw material and component suppliers, final product producers, distribution centers. Based on customer requirements, supply chain members collaboratively design, produce, and deliver products while attempting to achieve the optimal performance of the cohort of the chain (Safaei, Moattar Husseini, & Farahani, 2010; Zhang, You, Jiao, & Helo, 2009). As today's business competition is among supply chains, instead of individual firms, it is deemed important to design effective supply chains, which can help sustain competitive advantages for all chain members. This is well evidenced by the numerous articles reported for designing supply chains in the recent two decades (Gebennini, Gamberini, & Manzini, 2009; Ivanov, 2010).

As pointed out in (Gebennini et al., 2009; Ivanov, 2010; Sabri & Beamon, 2000; Simchi-Levi, Kaminsky, & Simchi-Levi, 2004; Thanh, Bostel, & Peton, 2008), the supply chain design's central decisions include supplier selection, facility location and capacities, customer demand allocation, raw material, component and product flows, which are at the strategic level. To cope with these decisions, researchers have proposed a myriad of valuable strategic supply chain design models. Most of these models treat each stage (or at most two) of the chain as a separate system, e.g., only procurement or only production or the integration of production-distribution; a few studies have addressed an integrated supply chain design from material procurement to production to product delivery (Sabri & Beamon, 2000; Li, Hendry, & Teunter, 2009). However, as revealed in industrial projects (Melo, Nickel, & Saldanha-da-Gama, 2005), companies wish the simultaneous consideration of all the three important stages in their supply chain design. This indicates that designing a supply chain by considering multistage and their interactions yields realistic solutions. In a recent review article based on the analysis of 33 survey-based studies, van der Vaart and van Donk (2008) point out that integrated supply chain design leads to higher supply chain performance. In view of the importance of considering multistage in supply chain design and the relative lack of models, in this study, we simultaneously consider procurement, production and distribution in the strategic supply chain design.

A bill of materials (BOM) is a very important product document and describes in detail product's constituent elements and

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their relationships. BOMs provide key information for coordinating activities between material procurement and production in a supply chain and are, thus, related to many complex supply chain inter-relationships (Yan, Yu, & Cheng, 2003). Researchers highlight that BOMs should be exploited to coordinate the behavior of suppliers with the production and distribution activities and should be considered as constraints in the strategic supply chain design (Arntzen, Brown, Harrison, & Trafton, 1995; Cohen & Lee, 1989; Melo, Nickel, & Saldanha-da-Gama, 2009). However, due to the difficulties in formulating BOM-related constraints in a mathematical model, there is a lack of models with the inclusion of BOM constraints (Vidal & Goetschalckx, 1997; Thanh, Bostel, & Peton, 2008; Melo et al., 2009). In this study, we consider BOMs in the development of the integrated model for strategic supply chain design and formulate BOM-related constraints.

Among the available supply chain design models, some consider one product (Li et al., 2009; Osman & Demirli, 2010, to name but three); some involve multiple products (Das, 2011; Safaei et al., 2010; Thanh, Bostel, & Peton, 2008; Yan et al., 2003). Designing supply chains for multiple products is more practical. The reason for this is that in practice, companies develop families of related products (so called product families) to fulfill diverse individualized customer requirements. Due to the similarities among customized products in a family, a supply chain is normally utilized to design and produce one product family (Huang, Zhang, & Liang, 2005). In this study, we consider multiple products in developing the integrated, strategic supply chain design model.

To summarize, this study focuses on the strategic design of supply chains for multiple products by considering procurement, production, distribution and their interactions and BOM-related constraints. A mixed integer non-linear programming (MINLP) model is developed. In order to solve the MINLP model, swarm intelligence is employed in this study. Swarm intelligence is a new category of the meta-heuristics, which is inspired by the collective intelligence of insect colonies or animal societies in their operational behavior (Bonabeau & Dorigo, 1999). One of the typical examples of intelligent swarms is the bee colony, which demonstrates an amazing intelligence when foraging for food sources. In this study, we, thus, employ a bee colony inspired algorithm, named artificial bee colony (ABC) algorithm. The ABC algorithm is originally introduced by Karaboga (2005) and becomes a popular choice for solving constrained optimization problems in comparison to the evolutionary computation thanks to its simple yet robust framework and implementation simplicity. The ABC algorithm is efficient in both exploration and exploitation of the search space because of its unique design of multiple roles and phases (Horng, 2011; Karaboga, Gorkemli, Ozturk, & Karaboga, 2014). In view of the advantage of the ABC algorithm for solving optimization problems, we develop an approach based on the ABC algorithm to solve the proposed MINLP model. The effectiveness and efficiency of the ABC-based solution approach is demonstrated through a comparison with other approaches, including LINDO (a commercial solver) and a genetic algorithm (GA)-based approach.

The rest of the paper is organized as follows. We formulate the MINLP integrated, strategic supply chain design model in Section 2 by identifying diverse constraints. This is followed by the proposed ABC-based solving approach in Section 3. Bicycle design and production is used to demonstrate designing supply chains using the MINLP model in Section 4. Also provided in this section is the comparison between the proposed ABC-based solution approach and LINDO, the GA approach. We conclude this paper in Section 5 by pointing out the limitations and identifying potential avenues for future research.

2. Model formulation

2.1. Problem context and decisions

A set of products is to be designed, manufactured, and distributed by a set of facilities, including suppliers, production plants, and distribution centers (DCs), which will form a supply chain. A production plant is responsible for the overall design and production activities, whilst suppliers are expected to be involved in design and production of intermediate components. Each facility has limited capacity in fulfilling its tasks. Together, they complete the product design, production, and distribution according to customer requirements. Consistent with the current global manufacturing practice, while the set of production plants belong to one company, the suppliers and DCs may not belong to the same company (Chung, Lau, Choy, Ho, & Tse, 2010; Kim & Kim, 2008). In addition, the company makes the decision on the plants, suppliers, and DCs to be included in the supply chain. As indicated by Anussornnitisarn, Nof, & Etzion, 2005; Dominiquez and Lashkari, 2004; Moon, Seo, Yun, & Gen, 2006, the above context where supply chains are formed is not uncommon in practice, especially when involving internationally operating companies.

In this study, the general decisions considered are related to the selection of supply chain facilities and the allocation of loading (e.g., component quantities) to these facilities. The specific decisions deal with: (i) the selection of specific suppliers, production plants, and DCs, (ii) the design tasks assigned to suppliers and plants, (iii) the amount of components and products to be produced and shipped among suppliers, plant, DCs, and customers, (iv) global capacity coordination for the involved suppliers and plants, and (v) distribution planning that determines optimal distribution channel and quantity. Taking into account these decision factors, we formulate the below MINLP model.

2.2. The MINLP model

Involving multiple products and multiple stages, the supply chain design problem requires a systematic approach to account for product-related characteristics, supply and demand matching, facility loading, and both inter- and intra-facility transactions. The supply chain designed should be cost-effective so that the total cost associated with design, production, holding inventory, and logistics can be reduced to a minimum level. In light of the above issues, the MINLP model attempts to minimize the total cost of a supply chain, subject to the capacities of suppliers, plants, and DCs, throughput constraints, and customer demand requirements as well. The model is formulated based on the following assumptions.

Assumptions:

1. Each plant is able to produce any arbitrary product mix;
2. Product fulfillment within a plant is divided into a finite set of sub-tasks, each being carried out by one or more than one supplier;
3. If a supplier undertakes a task of designing a component, it is also responsible for producing the component;
4. Each plant purchases components from multiple suppliers and each supplier serves several plants;
5. Each DC is opened for any arbitrary product mix;
6. DCs deliver all received products to customers (Note: Like many available supply chain design models, drop shipping is not considered in this study. Thus, DCs receive products and deliver them to customers.);
7. According to geographical locations, customers are grouped into different zones, forming customer zones (CZs);