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The CAT metaheuristic for the solution of multi-period activity-based supply chain network design problems

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A B S T R A C T

This paper proposes an agent-based metaheuristic to solve large-scale multi-period supply chain network design problems. The generic design model formulated covers the entire supply chain, from vendor selection, to production–distribution sites configuration, transportation options and marketing policy choices. The model is based on the mapping of a conceptual supply chain activity graph on potential network locations. To solve this complex design problem, we propose Collaborative Agent Team (CAT), an efficient hybrid metaheuristic based on the concept of asynchronous agent teams (A-Teams). Computational results are presented and discussed for large-scale supply chain networks, and the results obtained with CAT are compared to those obtained with the latest version of CPLEX.

1. Introduction

In recent years, the emphasis on trade globalization as well as the emergence of new economic powers such as the Brazil, Russia, India, and China (BRICs) brought forth new competitive challenges as well as new opportunities for growth and cost reductions. The ensuing mergers, acquisitions as well as supply chain reconfigurations involve a large number of complex inter-related supply chain network (SCN) design decisions that heavily impact company's competitive position, debt and profitability. Moreover, the large investments associated with these decisions require the consideration of a planning horizon covering several years. In such a context, companies seek to improve their profitability by generating economies of scale as well as making efficient use of capital while improving customer service (Cooke, 2007). Given the complexity and interdependence of supply chain network design decisions, it has been shown that the use of operations research techniques and tools such as mixed-integer programming models can result in significant returns (Geoffrion and Powers, 1995; Shapiro, 2008). Unfortunately, the problems to be modeled are so large and complex that even the best-of-breed commercial solvers are seldom able to solve real instances to optimality in a reasonable amount of time. Thus, the need for an efficient and flexible heuristic solution method arises.

A typical SCN design problem sets the configuration of the network and the missions of its locations. Some facilities may be opened, others closed, while others can be transformed using different capacity options. Each selected facility is assigned one or several production, assembly and/or distribution activities depending on the capacity options available at each location. The mission of each facility must also be specified in terms of product mix and facilities/customers to supply. Key raw-material suppliers must be selected. For each product-market, a marketing policy setting service and inventory levels, as well as maximum and minimum sales levels, must also be selected. The objective is typically to maximize net profits over a given planning horizon. Typical costs include fixed location/configuration costs, fixed vendor and market policy selection costs, as well as some variable production, handling, storage, inventory and transportation costs (Amrani et al. 2011).

The objective of this paper is, first, to propose a generic formulation of the multi-period SCN design problem based on the mapping of a conceptual supply chain activity graph on potential network locations, and, second, to propose an efficient hybrid metaheuristic based on a collaborative agent team (CAT) to solve large instances of this model. The rest of the paper is organized as follows. In Section 2, a general review of the relevant

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literature is provided. Section 3 defines the activity-based concepts required to model SCNs. Section 4 formulates the mathematical programming model to be solved. Section 5 outlines the solution approach developed to tackle the problem. Computational results are presented and discussed in Section 6, and Section 7 concludes the paper.

2. Literature review

Several modeling approaches can be used to formulate the supply chain network design problem. The simplest models available are appropriate to solve facility location problems (FLP), which can be either capacitated (CFLP) or uncapacitated (UFLP). Some formulations also impose single-sourcing (CFLPSS), i.e. they require that demand zones are supplied from a single facility. Since the publication of the original formulation published by Balinski (1961), several exact approaches and heuristics have been proposed to solve these single-echelon, single-product network design problems. Hansen et al. (2007) tackle very large instances of the CFLPSS with a primal–dual variable-neighborhood search metaheuristic that yields near-optimal solutions with an optimality gap not exceeding 0.04%. Several extensions or variants of the CFLP and CFLPSS have been proposed. Multi-product as well as multi-echelon models have been formulated and solved, usually by Benders decomposition (Geoffrion et al., 1974) or Lagrangean relaxation (Klose, 2000). These extended models are more difficult to solve than basic CFLP or CFLPSS models, yet they are simpler than the problem tackled in this paper. A recent review of the literature on facility location problems and their extensions is found in Klose and Drexl (2005).

In facility location models, the capacity of potential facilities is assumed to be predetermined. As capacity acquisition is a rather fundamental aspect of supply chain design problems, several authors investigated capacity expansion and relocation alternatives. Verter and Dincer (1992) discuss the relationship between facility location, capacity expansion and technology selection problems. Paquet et al. (2004) and M'Barek et al. (2010) consider several discrete facility capacity options for each location, while others such as Eppen et al. (1989) and Amrani et al. (2011) consider alternative site configurations (platforms), an approach also used in this paper. Following the observation by Ballou (1992) that the throughput–inventory relation in facilities is not linear but rather concave, due to risk-pooling effects, some recent papers such as Martel (2005) and Amrani et al. (2011) also consider economies of scale in inventory costs. Variable costs are generally assumed to be linear.

In several recent applications found in the literature (Elhedhli and Goffin, 2005; Romeijin et al., 2007), it is assumed that the type of activities that can be performed over a given location are predetermined (such as production, assembly or warehousing). Lakhal et al. (1999) introduced the concept of activity graph to map the succession of sourcing, manufacturing, warehousing and transshipment activities that constitutes the company's supply chain. In these models, the actual mapping of activities on locations is determined by the model. Supply chain network design models based on activity graphs were subsequently proposed by Vila et al. (2006) and M'Barek et al. (2010). Although several applications consider a single period, some authors included multiple production and demand seasons in their model (Arntzen et al., 1995; Dogan and Goetschalckx, 1999). Multi-season models anticipate variations in demand and activity levels during a planning horizon, whereas multi-period models consider several design adjustment cycles over a long-term horizon. An integrated multi-season model is found in Martel (2005), while a multi-period model is proposed in Paquet et al. (2008).

The design of sustainable supply chain networks has also recently been addressed. Pan et al. (in press) explore approaches to reduce greenhouse gas emissions, and Chaabane et al. (2012) develop a design model integrating tradeoffs between environmental and economic objectives. Chouinard et al. (2008) and Easwaran and Üster (2010) consider the design of closed-loop supply chains, and a review of the literature on reverse logistics network design is found in Ilgin and Gupta (2010). There is also a growing interest in SCN design models under uncertainty. Vidal and Goetschalckx (2000) consider random variables *a posteriori* in a post-optimization evaluation step. Santoso et al. (2005) propose a stochastic programming approach where design choices are associated with first stage variables, and network flow variables provide the recourses necessary to guarantee the solution feasibility. A thorough review of SCN design under uncertainty is provided in Klibi et al. (2010).

For the sake of simplicity, our model does not include modeling components related to international dimensions such as the inclusion of transfer prices, import/export duties and income taxes. International adaptations of supply chain network design models have been proposed by Arntzen et al. (1995), Vidal and Goetschalckx (2001), Martel (2005), Vila et al. (2006) and M'Barek et al. (2010). The modifications required to adapt the model presented in this text to the international context are straightforward. A review of the literature on global supply chain network design is found in Meixell and Gargeya (2005).

Several solutions approaches have been proposed and tested to solve supply chain network design models. Some of the most popular methods are Benders decomposition (Geoffrion et al., 1974; Dogan and Goetschalckx, 1999; Paquet et al., 2004; Cordeau et al., 2006), Lagrangean-based methods (Klose, 2000; Elhedhli and Goffin, 2005; Amiri, 2006), successive linear programming or mixed-integer linear programming with valid cuts (Vidal and Goetschalckx, 2001; Martel, 2005; M'Barek et al., 2010), and Dantzig–Wolfe decomposition (Liang and Wilhelm, 2008). Several metaheuristic solution procedures were also proposed to solve SCN design models based on variable-neighborhood search or tabu search (Amrani et al., 2011), iterated local search (Cordeau et al., 2008), simulated annealing (Jayaraman and Ross, 2003), hybrid genetic algorithms (Syarif et al., 2002; Zhou et al., 2002; Altiparmak et al., 2006, 2009, Lin et al. 2009), memetic algorithms (Pishvaee et al., 2010) and particle swarm optimization (Bachlaus et al., 2008). It should be noted that all of these metaheuristic procedures assume single sourcing or single assignment constraints for all locations in the network. While this kind of formulation is harder for MIP-based approaches to solve, it circumvents the well-known weakness of most metaheuristics in dealing with the continuous variables used to model flows.

The effectiveness of OR-based methods to improve a SCN's performance, reduce costs and increase profitability is well documented in the literature (Geoffrion and Powers, 1995). For example, Camm et al. (1997) report that Procter & Gamble's SCN reengineering yielded a pre-tax annual cost reduction of over 200 millions USD. Similar projects have been successfully concluded at Elkem (Ulstein et al., 2006), IBM (Denton et al., 2006), and BMW (Fleischmann et al., 2006).

The model proposed in this paper is an integrated reformulation and generalization of existing supply chain network design models. Using the activity-based supply chain representation of Lakhal et al. (1999), it builds on the notions of facility configuration options and inventory-throughput functions presented in Martel (2005). It also incorporates demand shaping decisions based on the concepts of market policies introduced in Vila et al. (2006) and M'Barek et al. (2010). The model also includes original extensions such as the consideration of transportation options. It covers the entire supply chain, from vendor selection to site