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Dynamic design and re-design of multi-echelon, multi-product logistics networks with outsourcing opportunities: A computational study

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ABSTRACT

We address the problem of designing/redesigning a multi-echelon logistics network over multiple periods. Strategic decisions comprise opening new facilities and selecting their capacities from a set of available discrete sizes. Capacity expansion may occur more than once over the time horizon both at new locations and at existing facilities. In addition, logistics decisions involving supplier selection, procurement, production, and distribution of multiple products are to be made. The latter also involve the choice of transportation modes with limited capacities. Finally, a strategic choice between in-house manufacturing and a mixed approach with product outsourcing is to be taken. We propose a mixed-integer linear programming model and develop additional inequalities to enhance the original formulation. To gain insight into the complexity of the problem at hand, an extensive computational study is performed with randomly generated instances that are solved with standard mathematical optimization software. Useful managerial insights are derived from varying several parameters and analyzing the impact of different business strategies on various segments of the logistics network.

1. Introduction

Logistics network design (LND) is the strategic planning process for optimizing the configuration of a supply chain. In broad terms, LND involves determining the optimal number and location of facilities (e.g., manufacturing plants and warehouses), allocating capacity and technology requirements to facilities, and deciding on the flow of products throughout the supply chain such that customer demands are satisfied at minimum cost or maximum profit.

Depending on the actual business requirements, a company may consider either redesigning its supply chain or designing a new chain in order to align its logistics network with new business conditions or to meet new strategic objectives. Logistics network re-design (LNRD) is typically prompted by changing market and business conditions, frequently in conjunction with increased cost pressure and service requirements. These factors compel companies, for example, to expand or restructure their supply chain operations. If a company grows through external acquisitions, network re-design addresses the integration of acquired operations to fully exploit all benefits and synergies at supply chain level. In contrast, the need for designing a new network arises when a company enters new geographical markets or grows into new product segments. So-called "greenfield" approaches are less frequent compared with re-design projects. However, a company may wish to evaluate how far its existing logistics network deviates from an optimal configuration.

The role of LND and LNRD has become even more prominent in today's business environment, as companies have to cope with a variety of challenges in order to deliver outstanding supply chain performance. Strategic network decisions affect all levels of supply chain management and provide the framework for successful tactical and operational supply chain processes. As highlighted by Ballou (2001) and Harrison (2004, chap. 1), a network re-design project can result in a 5–15 percent reduction of the overall logistics costs, with 10 percent being often achieved.

In this paper, an integrated and comprehensive view of the supply chain is taken by considering raw material suppliers, manufacturing facilities, warehouses, transportation channels, and customer zones as shown in Fig. 1. In an LNRD approach, a network is already in place with a number of plants and warehouses being operated at fixed locations (these are highlighted by the dashed lines in the figure). A variety of decisions have to be made regarding facility location and logistics functions along the supply chain. The former concern opening new plants and/or warehouses at potential sites (the facilities without dashed lines in Fig. 1) and

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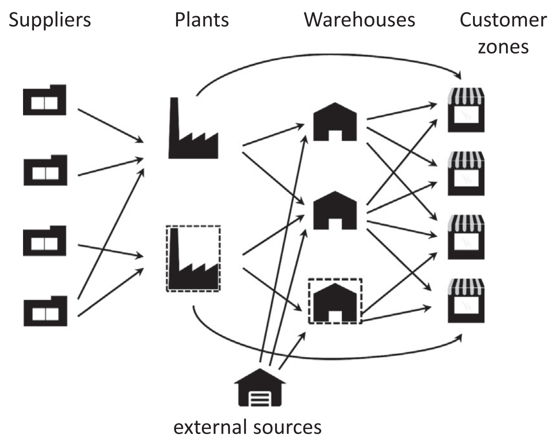

Fig. 1. Possible configuration of a multi-echelon logistics network.

selecting their capacity levels from a set of available discrete sizes. This is motivated by the fact that capacity is often purchased in the form of equipment which is only available at a few discrete sizes. As strategic planning for multiple time periods is considered, capacity can be acquired more than once over the time horizon both at new and existing locations. Capacity contraction is also possible by closing existing plants and/or warehouses. These options are attractive when adjustments in the network configuration of a company are required to enable future growth in new markets or to meet increasing product demand in current markets. In an LND approach, by contrast, the scope of the location decisions is limited to deciding on the optimal size, number, and location of new facilities.

Logistics decisions, the second group of key business decisions, involve supplier selection in conjunction with procurement as well as production and distribution decisions. Furthermore, a strategic choice between in-house manufacturing, outsourcing or a mixed approach is to be taken.

In the network depicted in Fig. 1, multiple types of products are manufactured at plants by processing sub-assemblies and components, hereafter called raw materials. The latter can be procured from various suppliers taking into account their availability and cost. Finished products can be delivered to warehouses or shipped directly to customer zones. The flow of goods throughout the network and the use of transportation modes are to be determined in each time period. In addition, end products can also be purchased from external sources and consolidated at the warehouses. The objective is to determine the network configuration over a planning horizon so as to minimize the total cost.

The contribution of this paper is threefold. First, we propose a new mathematical model that significantly generalizes several existing network design models. This is accomplished through the integration of various strategic features of practical relevance into a single model. The new model can be used both for redesigning a logistics network that is already in place and for designing a new supply chain. Applications can be found in a number of industrial contexts, e.g. consumer goods industry. Second, we perform a computational study on a large set of randomly generated instances and assess the impact of various problem characteristics on the ability of state-of-the-art optimization software to solve problem instances within a reasonable time limit. This analysis is performed using the proposed model strengthened with additional valid inequalities. Third, valuable managerial insights are derived that illustrate the far-reaching implications of strategic network design on different supply chain segments (location, supply, manufacturing, distribution, outsourcing). Without the support of the model developed in this paper it would otherwise be difficult to obtain most of these insights. Given the typically high investment volumes and the limited reversibility of strategic decisions, it is essential for stakeholders to perceive the impact of (re-)design and logistics decisions on supply chain performance.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature dedicated to LND/LNRD and describe its relation to our new model. Section 3 introduces a mixed-integer linear programming formulation for logistics network design and re-design. In addition, valid inequalities are proposed to enhance the original formulation in an attempt to strengthen its linear relaxation bound. Section 4 reports on the computational experiments carried out and the managerial insights gained from randomly generated instances involving the reconfiguration of existing logistics networks as well as the design of new networks. Finally, in Section 5, conclusions are provided and directions for future research are identified.

2. Literature review

Beginning with the pioneering work of Geoffrion and Graves (1974) on multi-commodity distribution network design, a large number of optimization-based approaches have been proposed for the design of logistics networks as shown by the recent surveys of Melo, Nickel, and Saldanha-da-Gama (2009) and Mula, Peidro, Díaz-Madronero, and Vicens (2010). These works have resulted in significant improvements in the modeling of these problems as well as in algorithmic and computational efficiency. One of the reasons that contributes to such a large number of literature references is the variety of characteristics that can be taken into account in LND problems: type of planning horizon (single or multi-period), facility location and sizing, number of echelons and type of distribution levels, multi-stage production taking the bill of materials (BOM) into account, and transportation mode selection, among others.

Although the timing of facility locations and expansions over an extended time horizon is of major importance to decision-makers in strategic network design, the majority of the literature addresses single-period problems, e.g., Babazadeh, Razmi, and Ghodsi (2012), Cordeau, Pasin, and Solomon (2006), Elhedhli and Gzara (2008), Eskigun et al. (2005), Olivares-Benitez, González-Velarde, and Ríos-Mercado (2012), Sadjady and Davoudpour (2012). Our research is different in that a multi-period planning horizon is considered. Unlike our work, in some multi-period LND problems facility sizing is static, meaning that facilities cannot have their capacities expanded or contracted over the planning horizon. The model proposed by Gourdin and Klopfenstein (2008) falls into this category.

We will focus next on multi-period LND and LNRD problems with dynamic facility sizing decisions. In particular, we will discuss the extent to which the features of the model to be detailed in Section 3 differ from those reported so far in the literature.

To re-design a two-layer network, Antunes and Peeters (2001) suggest a modeling framework that allows opening new facilities and closing existing locations, as well as expanding and contracting capacity. Budget constraints are taken into account over the time horizon. Simulated annealing is used to find feasible solutions.

Melo, Nickel, and Saldanha da Gama (2006) study the re-design of a multi-echelon network considering facility expansion and contraction. This feature is modeled through moving capacity from existing facilities to new facilities over the planning horizon. Network re-design decisions (opening, closing, and relocating facilities) are subject to budget constraints in each time period. General purpose optimization software is used to solve small and medium-sized problem instances. Melo, Nickel, and Saldanha-da-Gama