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A linear relaxation-based heuristic approach for logistics network design

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ABSTRACT

We address the problem of designing and planning a multi-period, multi-echelon, multi-commodity logistics network with deterministic demands. This consists of making strategic and tactical decisions: opening, closing or expanding facilities, selecting suppliers and defining the product flows. We use a heuristic approach based on the linear relaxation of the original mixed integer linear problem (MILP). The main idea is to solve a sequence of linear relaxations of the original MILP, and to fix as many binary variables as possible at every iteration. This simple process is coupled with several rounding procedures for some key decision variables. The number of binary decision variables in the resulting MILP is small enough for it to be solved with a solver. The main benefit of this approach is that it provides feasible solutions of good quality within an affordable computation time.

1. Introduction

Logistics network design is concerned with many strategic and tactical decisions. We consider a mixed integer linear programme (MILP) for designing and planning a complex supply chain over a horizon of a few periods (typically 5 years). An optimal configuration must enable products to be produced and delivered to the customers at the lowest cost while satisfying a required service level.

It is widely considered as unrealistic to handle universal models including concerns about logistics, risk management, finance, social and environmental issues, etc. As pointed out in Min and Zhou (2002), one has to know which essential components must be managed and then establish specific supply chain goals. In this work, we focus on the logistics issues and, more particularly, on the *location* and *allocation* decision variables: location of warehouses and production plants, allocation of warehouses to production plants, allocation of customer demand points to warehouses, definition of the material flows between the nodes of a complex logistics network. The MILP under consideration can be viewed as a facility location problem, with multiple facilities, periods and commodities, and additional constraints. Although a few tactical issues are addressed by the model, the problem is clearly a strategic one.

To make sure that the proposed solutions are compatible with the industrial context and robust toward uncertainties in some parameters (costs, demands), it is strongly advised to run several computations of the model, with various network configurations or logistics scenarios. Thus, the model is likely to be run repeatedly until a strategic decision is taken. One prerequisite is that the underlying optimisation methods provide very good approximations of the optimal solution within an acceptable amount of time.

We propose a heuristic algorithm based on successive linear relaxations of location decision variables, followed by correction procedures. The main contribution of this method is to yield feasible solutions of good quality within a limited computation time. The paper is organised as follows. In Section 2, we recall the main concepts of supply chain design and planning and introduce the optimisation problem. In Section 3, we present the linear relaxation-based algorithm. In the computation experiments of Section 4, our goal is to evaluate the performance as well as the limitations of the approach.

2. A dynamic model for logistics network design

2.1. A brief review of the literature

The multi-period planning of a supply chain is an NP-hard problem that has been addressed by many authors in the recent and abundant literature. There is such a large variety of enterprise logistics networks that completely generic models would probably not fit any company. The most recent models include many features with the idea of reflecting some real cases or focusing on some particular aspects of the location problems.

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Among the most widespread characteristics in the recent models are:

- a supply chain with multiple echelons and multiple products or families of products,
- dynamic models where the data and variables may change at every period,
- complex product flows, with an exchange of products between plants or warehouses, direct deliveries to some customers, reverse logistics, re-manufacturing, etc.
- a variety of constraints: competition or budget constraints, etc.
- complex cost structures: fixed and variable costs, linear or non-linear costs,
- hybrid strategic/tactical models with inventories: average, safety or cyclic inventories.

Dias, Captivo, and Climaco (2006) worked on the re-engineering of a network composed of facilities and customers. The authors suppose that facilities can be open or closed and can reopen more than once during the planning horizon. The model is solved by primal–dual heuristic methods. Melo, Nickel, and Saldanha da Gama (2006) aimed at relocating the network with expansion/reduction capacity scenarios. Capacity can be exchanged between an existing facility and a new one, or between two existing facilities under some conditions. Vila, Martel, and Beauregard (2006) proposed a dynamic model in a much more specialised context. They considered an application in the lumber industry, but their model can be applied to other sectors.

The methods for solving logistics network planning and design use the classical tools of operations research. The exact methods include branch-and-bound, Benders decomposition or the use of a commercial solver (Bidhandi, Yusuff, Ahmad, & Bakar, 2009; Canel, Khumawala, Law, & Loh, 2001; Hamer-Lavoie & Cordeau, 2006; Martel, 2005; Melo et al., 2006).

As emphasised by Melo, Nickel, and Saldanha da Gama (2009), when the number of discrete variables is large, realistically sized problems can only be solved with a heuristic method. Our work falls into this category of problem. Most of the metaheuristic approaches are proposed for basic models like static models for simple network planning. Filho and Galvpo (1998) used tabu search to solve a concentrator location problem. Syam (2002) mixed simulated annealing and Lagrangean relaxation to solve a 3-echelon problem. Other authors have used genetic algorithms (Gong, Gen, Yamazaki, & Xu, 1997; Jaramillo, Bhadury, & Batta, 2002).

Surprisingly enough, few heuristic methods have been reported in the specialised literature, although they seem to be efficient for the most complex problems. The most common heuristic methods use some "add" and "drop" procedures (Saldanha da Gama & Captivo, 1998), or rely on primal–dual methods (Dias et al., 2006) or Lagrangean relaxation (Hinojosa, Kalcsics, Nickel, Puerto, & Velten, 2008; Hinojosa, Puerto, & Fernández, 2000; Pirkul & Jayaraman, 1998). Heuristic methods based on simple neighbourhood structures and local improvements are seldom used because of the heterogeneity of the entities considered (suppliers, plants, warehouses, transport, customers, machines). More efficiency might be achieved by recent metaheuristic methods that combine various neighbourhoods within adaptive algorithms.

2.2. Description of the problem

We consider a network composed of four layers, like the one depicted in Fig. 1.

The first layer consists of a set of potential first tier suppliers that provide the company with raw materials. Production steps composed of plants make up the second layer. Product storage and distribution steps, carried out by warehouses, are the main constituents of the third layer. Finally, the fourth layer is composed of retailers or final customers. We adopt a flexible network structure: products can be transferred between plants or delivered directly from plants to important customers. This approach enables us to model various practical situations. For example, we can deal with the second tier suppliers once the first tier suppliers have been selected. In this case, the first tier suppliers should be considered as production centres in the second layer. Some other changes in the network configuration would require a modification of the current mathematical model, but the main conclusions of this paper remain valid for many location problems in the context of a complex supply chain.

A complete description of the problem and the mathematical model are presented in Thanh, Bostel, and PTton (2008) and can be found in the Appendix. In this paper, we only recall the main characteristics of the model.

We consider a multi-commodity supply chain where every product has its own bill of materials. The manufacture of these products may be decomposed into different steps performed in different production plants. Every plant or warehouse has a limited capacity along with lower and upper limits for the level of utilisation (running a plant at 1% or at 100% of its capacity is not authorised). We also model the possibility of increasing the capacity of an existing facility by building some physical extensions, called capacity options.

Our purpose is to make strategic decisions over a multi-period planning horizon. These decisions concern the selection of suppliers, the opening or closing of facilities, capacity planning for open facilities, and production and distribution management. Production management consists of allocating manufactured products to open plants and managing subcontracted products (we suppose that the company can subcontract a part of its production). Distribution management consists of allocating the customers to open or rented warehouses. The model does not include any single-sourcing constraint. Some inventory management aspects are also included as they influence strategic decisions such as capacity planning. We suppose that the inventories are planned only in warehouses, not in plants.

The mathematical model includes four types of binary decision variables, most of which are related to the location of facilities. Let us define the binary variables x_i^t that have the value 1 if a facility i is active at period t, and 0 otherwise. Depending on the context, a variable x_i^t stands for a supplier, a plant or a warehouse. A supplier is said to be active if it delivers at least one raw material. A plant or a warehouse is active if it is open in the corresponding period.

As shown in Thanh et al. (2008), variables x_i^t concerning plant and warehouse locations are the core of the model. They have a direct influence on the largest part of the objective function. Other binary variables concern the capacity options and the selection of suppliers. The MILP also includes continuous decision variables that model the product flows along the network (quantities of products transferred from the suppliers to the plants, the warehouses and the customers). Since the remainder of the paper only uses variables x_i^t, we do not give more details about other variables. The interested reader will find them in the Appendix.

The cost structure consists of two parts. The *fixed costs* are related to the supplier selection, the opening, the closure or the extension of facilities and, finally, to the running of existing facilities. The *variable costs* are associated with the main logistics operations: production, storage, transportation between entities and distribution to the customers. We consider one linear objective function, which is the sum of all the fixed and variable costs. Without loss of generality, this function is considered to be time-independent.