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Simultaneous product family and supply chain design: An optimization approach

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ABSTRACT

This paper deals with the difficult problem of joint product family and supply chain design. We present a general model that simultaneously considers the construction of the bill of materials and the design of the supply chain network. For the bill of materials, product, sub-assembly and component substitution possibilities are considered. For the supply chain network, facility and distribution center location are considered as well as the choice of suppliers. A Mixed Integer Linear Program (MILP) model is proposed. The MILP formulation is solved optimally for medium-sized instances. For larger instances, two heuristics derived from the MILP are designed. These methods are computationally tested on various instances from a generator conceived for this purpose. The modelling of product substitution possibilities through product transformation permits the solving of large size instances that are now adequate for real problems.

1. Introduction

To respond efficiently to customer demand, companies propose diversified products. This diversity affects design, production and distribution processes. In this context, a great challenge is how to design the product family and its supply chain simultaneously. This global optimization is the way to efficiently manage the trade-off between standardization, which reduces costs, and diversification, which will potentially increase sales.

The contribution proposed in this paper is an extension of a project that is carried out with an industrial partner. Our partner designs and manufactures large projects that include electro-mechanically products that need to be adapted for each situation. The work presented in this paper covers a new area for this practitioner: the joint design of product family and supply chain.

Joint product family and supply chain design requires that a company creates a product family with a number of configuration possibilities. Within a product family, we need to know which possibilities (modules) are equivalent in terms of function and which are upgrades. This information may be difficult to obtain and sometimes not available. In the present case, our partner tries to evaluate the pertinence of this future avenue. Consequently, we use academic data in our study that are as close as possible to our partner's data.

Production and logistical constraints have already been considered in product family design through the concept of mass customization, developed by Pine (1993) and Nepal et al. (2012). It is now widely accepted that this design technique can realize a large variety of product designs at minimum cost, by considering product commonality, for example Thonemann and Brandeau (2000), Shafia et al. (2009). The next step has been to develop optimization techniques to determine the makeup of product families (Briant and Naddef, 2004; Agard and Penz, 2009).

More recently, product family design and supply chain design have been considered simultaneously. This has resulted in an awareness of the need for global optimization, as has been highlighted by Baud-Lavigne et al. (2012) and Chen (2010). These authors show that decisions on product design have a major impact on supply chain design, and vice-versa. Baud-Lavigne et al. have compared simultaneous design with sequential design, and found that a gain of 1–25% can be expected when the product family and the supply chain are optimized together. Supply chain

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design models that consider the bills of materials (BOMs) of products are recent arrivals that have been rarely studied to date. A single-period, multi-product, multi-level model has been proposed by Paquet et al. (2004), and a multi-period model has been presented by Thanh et al. (2008). In their models, the BOMs are fixed, which means that only the supply chain is optimized. Other studies on supply chain design include Yan et al. (2003), which highlights the role of the BOM in supplier selection, Cordeau et al. (2006), which focuses on resolution methods, such as Benders decomposition and valid inequalities, Schulze and Li (2009), which integrate the choice of modules, and Hammami et al. (2009), which deals with relocation issues.

Very few studies address the simultaneous optimization of the product family and the supply chain. Appelqvist et al. (2004) present a survey on product and supply chain design, and two approaches are proposed in the literature. In the first, the authors define the best product family for meeting market needs using a generic BOM for the design of the product family (Lamothe et al., 2006; Zhang et al., 2008). In these formulations, BOMs are determined in such a way as to respect assembly constraints. In the second approach, the authors consider that the final products are determined, but the BOMs remain more or less flexible. El Hadj Khalaf et al. (2010) consider a modular design problem for which all assembly options are possible, and yet the final assembly time is constrained. Another approach is to define several alternative BOMs (ElMaraghy and Mahmoudi, 2009) with one being selected for the optimal solution. Unfortunately, this approach needs complete enumeration of all the product configuration options. Nevertheless, this approach facilitates both the mathematical formulation and the solution search. Recently, Chen (2010) proposed an integrated model for product family and supply chain design. Its main drawback is the large number of decision variables involved, which makes large problems difficult to solve.

Our main contribution in this paper is to provide a mixed linear programming (MILP) model for the global product family and supply chain optimization problem, which extends those already proposed in the literature. We achieve this by extending the model proposed in Paquet et al. (2004) to include substitution possibilities. The second objective of the paper is to develop heuristics which yield good solutions (less than 1% from the optimal solution) and save time. Finally, for instances that are not tractable with the method as defined, we propose a heuristic based on the linear programming relaxation of the MILP formulation.

The paper is organized as follows. Section 2 describes the problem and gives a mathematical formulation. Our method and a heuristic alternative are presented in Section 3. Experiments are performed to test these propositions. Section 4 concludes the paper and provides some perspectives on the topic.

2. An optimization model for joint product and supply chain design

2.1. Model description

In product family design, the challenge is to precisely define the BOM for each final product in the product family. This BOM must take into account the sub-assemblies and components of each of the products. These sub-assemblies and components may also make up other products in the family. An example of a BOM is given in Fig. 1a that considers two products, $P1$ and $P2$. These two products each comprise two sub-assemblies. $P1$ is composed of sub-assemblies A and B, while $P2$ contains sub-assemblies A' and B'. A and A' (resp B and B') are sub-assemblies that use some similar components. The sub-assemblies are composed of components 1–5.

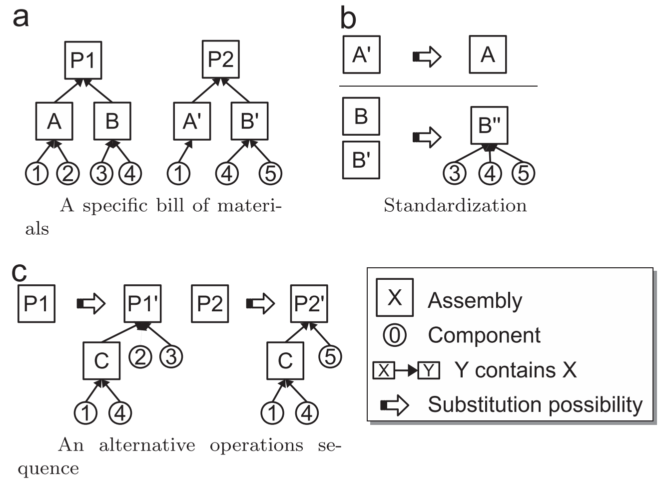

Fig. 1. A bill of materials and the three substitution possibility types.

In defining the BOM, substitution possibilities can be expressed through explicit equivalences between assemblies. Three types of substitution are considered:

Standardization: A component (or sub-assembly) can be upgraded by another component that has more functionalities or is of better quality. On the one hand, individual parts may be more expensive to buy, to produce, or to transport, and so the variable costs may increase. On the other hand, there is a decrease in diversity, which allows for better economies of scale. An illustration is provided in Fig. 1b. Sub-assembly A' can be replaced by A, B and B' can be replaced by a new sub-assembly, B''.

Externalization: A sub-assembly can be bought directly from a subcontractor. The production line is avoided, and so fixed costs are minimized, but variable costs may increase because the subcontractor has had to invest in the purchase. This normally means that each unit will be sold at a higher price than if it were made internally. In the example in Fig. 1a, sub-assembly A or B can be replaced by a component bought from a supplier.

Alternative operating sequence/product decomposition: Other component assembly sequences can result in better commonality without necessarily changing costs. Fig. 1c presents a sequence in which sub-assembly C has a better commonality without adding functions.

These possible substitutions of sub-assemblies or components in the BOM introduce a difficulty in terms of modeling, however. A typical way to express substitution is to use the BOM as a decision variable. This approach leads to quadratic constraints between the BOM and the production decision variables in most supply chain design models. Another approach, proposed in Chen (2010), is to use decision variables to express precisely how much of each alternative is used in each assembly produced, although this results in a considerable number of decision variables. In our model, we simplify this approach by considering substitution through product transformation. When part X can be replaced by part Y, a virtual process can transform X into Y. Then, a mixture is created in a plant containing an amount of X that is made up of the actual X parts and the alternatives that have been transformed into Y. This modeling allows substitution, while keeping the formulation light. In fact, the number of additional variables is exactly equal to the number of substitution possibilities.

For the supply chain design, we consider a generic supply chain, as depicted in Fig. 2, in which there are four layers: