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A matheuristic for aggregate production–distribution planning with mould sharing

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ABSTRACT

This paper discusses the aggregate production–distribution problem for a manufacturer of plastic products that are produced using injection moulding. For each product, only a single mould is available, but by exchanging moulds between plants, it is possible to produce any product at any plant. This mould sharing offers opportunities for cost savings but complicates the aggregate production–distribution planning. We present mixed integer linear programming formulations for this planning problem, and a matheuristic solution approach based on these models. The main goal of this aggregate planning tool is to quantify the opportunities that mould sharing offers to the plastics manufacturer. Computational experiments based on a real-life dataset confirm that mould sharing can reduce the production–distribution total cost with about 10%, and that the suggested matheuristic is capable of generating solutions that capture most of this significant savings potential.

1. Introduction

The increasing pressure to reduce total logistics costs is forcing supply chain managers to rethink production–distribution policies and make best use of their assets across multi-facility networks. This means that they have to embrace new logistics concepts and are confronted with more complex planning problems. This paper develops mathematical models for such an integrated production–distribution aggregate planning problem, based on the case of a large manufacturer of plastic products. These models are then used in a mathematical programming-based heuristic solution approach (or 'matheuristic' Maniezzo et al., 2010).

Given its practical importance and academic relevance, researchers have been investigating aggregate production planning in a multi-site environment, inspired by real-life cases from various industries. There is an extensive literature on multi-facility, multi-product, multi-period aggregate production–distribution planning, describing many different problem aspects and complications, and using various solution methodologies ranging from linear programming solvers to metaheuristics.

As in this paper, mixed integer programming formulations are often used in the existing literature. Dhaenens-Flipo and Finke (2001) propose a network flow model with relatively few binary variables for a manufacturer of metal items. A model with varying time scales is presented by Lin and Chen (2007) for a TFT-LCD manufacturer. Kanyalkar and Adil (2007) consider a consumer goods company and solve mixed integer linear goal programming models with different time grids heuristically. Gnoni et al. (2003) augment a mixed-integer linear programming approach with simulation to deal with demand uncertainty for a braking equipment manufacturer in the automotive industry. Along the same lines, Safaei et al. (2010) propose a hybrid mathematical-simulation model in which the simulation is used to reflect dynamics of real-world systems. Leung et al. (2007) have adopted robust optimization to deal with uncertainty for an application in the apparel industry. Similarly, Mirzapour Al-e-hashem et al. (2011) propose a robust multi-objective model in a case study from the paper industry.

Since large-scale problems cannot be tackled with mathematical programming solvers, metaheuristics are increasingly used in the literature to solve such large-scale problem instances. For more details, we refer to recent examples such as the artificial bee colony metaheuristic of Pal et al. (2011) and the genetic algorithm of Fahimnia et al. (2012).

In the existing literature, the possibilities of what products can be produced at which plants is usually given, and the decision is to allocate production volumes to the different plants. Whenever production has to be done in any plant, this often involves a setup

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or changeover cost, such that binary decision variables are needed next to the (continuous) production volume variables. The complication in the problem we are studying is in the fact that these binary variables are not independent for the different plants. This is due to the fact that the products are produced using injection moulding, such that a certain product can only be produced when the mould is available at the plant. Therefore, the binary variables at the different plants are linked through constraints that 'track' where the mould is. This complicates both the modeling and solution approaches a lot. To the best of our knowledge, the only article that contains this complication is that of Aghezzaf (2007). That paper also considers aggregate planning for injection moulding production in multiple facilities. A mixed integer linear programming model is presented that allocates moulds to plants across the planning horizon. Lower and upper bounds for the model are generated using Lagrangian relaxation and linear programming duality. Our paper contributes to the literature by presenting a more generic model that allows more flexibility in exchanging the moulds. Aghezzaf (2007) only allows moulds to be transferred from one plant to another at the end of a period, such that a mould is only available in a single plant during a period. Because time buckets in aggregate planning are reasonably large (typically one month), this is too restrictive and therefore we allow multiple mould moves within a period. Further, we explicitly take the loss of productive time for moulds being transferred into account. Finally, we offer a novel solution approach and show that it is capable of solving large real-life instances.

The remainder of the paper is structured as follows. After a more detailed problem description, the mathematical models are presented in Section 2. These models are used in the matheuristic described in Section 3. Section 4 illustrates the proposed solution methodology with a small-scale example, whereas Section 5 contains the results of the large real-life instance. Section 6 concludes this paper and gives avenues for further research.

1.1. Problem description

The supply chain under consideration in this paper consists of three stages, namely production plants, distribution warehouses and customers. The design of the network, i.e. the number and location of plants and warehouses, is given, such that the problem at hand is an allocation problem at the tactical level, i.e. deciding which products to produce where and through which warehouse products should be shipped to the customers. Products are being produced using injection moulding. Each stock-keeping unit (SKU) is made from its unique mould. The moulds can be exchanged between the different plants such that each SKU can be manufactured in any plant as soon as the corresponding mould is present. However, since the moulds are very expensive compared to the value of the products being produced on them, only a single mould is available per SKU. Therefore, only a single plant can produce a certain SKU at any given time, depending on whether or not the mould is present in the plant.

The European branch of the global manufacturer in case, having plants, warehouses and customers spread across Europe, has always produced each SKU at a single location so far. This means that moulds always stay in the same plant and are not exchanged between multiple plants. Because of changes in the product mix being demanded across their European market, and because of the increasing pressure to reduce costs, the company is reconsidering this strategy and wants to quantify the savings potential of mould sharing. If a mould always stays in the same plant, large volumes of the (low-value) product have to be transported from that plant to customers across the whole of Europe. By sharing the mould across plants, production can occur closer to the final market and transportation costs decrease significantly. On the other hand, mould sharing increases costs because (i) the variable manufacturing cost can be higher than in the mould's 'home' plant, and (ii) handling costs may be higher in the warehouses. Also, the transportation of the moulds themselves and the overhead for coordinating the mould exchanges incur extra costs.

The modeling and solution approach presented in this paper is capable of making this cost trade-off, while also taking into account capacity restrictions in both plants and warehouses. These capacity restrictions may force certain volumes of products to be allocated to a production–distribution combination that is more expensive (if capacity at the cheapest option is depleted). Further, the capacity restrictions could also necessitate producing certain volumes of (seasonal) products beforehand and keeping them in inventory to cover peak demand periods. The resulting inventory holding costs are also taken into account in the overall cost trade-off. The proposed model and solution approaches will help providing the answer to the company's question about the savings potential of increasing flexibility by allowing the possibility of sharing moulds across different plants.

2. Mathematical model

In this section, we present mathematical models for the multi-product multi-period aggregate production–distribution planning problem. As explained above, these models will be able to make the trade-off between the distribution cost savings that mould sharing enables with the additional costs they incur, all within the limited production and warehousing capacities of a given production–distribution network.

We propose two mathematical models for exploiting the possibility of sharing moulds between plants. The first model explicitly traces the movements of the model using binary variables that capture the from–to moves a mould makes. The second model tries to take advantage of the fact that the mould move cost and move time are assumed constant between any two pairs of plants. This second model does not explicitly follow the moulds, but merely counts the number of moves instead.

The mathematical models presented here consider a time horizon of T periods (indexed by t), a set of SKU's S (indexed by s), a set of plants P (indexed by p), a set of warehouses W (indexed by w) and a set of customers C (indexed by c). All volumes are expressed in numbers of pallets, which is appropriate for the aggregate, tactical planning level.

The parameters in the model are the following:

- wh number of working hours available in a period
- nm_p number of machines available in plant p
- pt_{sp} production time for a pallet of SKU s in plant p (hrs/pallet)
- pc_{sp} production cost for a pallet of SKU s in plant p (euro/unit)
- il_{sp} 1 if the mould of SKU s is initially located in plant p, 0 otherwise
- mt_{spq} time needed to move the mould of SKU s between plants p and q (hrs/move)
- mc_{spq} cost for moving the mould of SKU s between plants p and q (euro/move)
- tc_{pw} transportation cost from plant p to warehouse w (euro/pallet)
- sc_w storage cost in warehouse w (euro/pallet/period)
- $scap_w$ storage capacity of warehouse w (pallets)
- hc_w handling cost in warehouse w (euro/pallet)
- $hcap_w$ handling capacity of warehouse w (pallets/period)
- tc_{wc} transportation cost from warehouse w to customer c (euro/pallet)
- d_{sc}^t demand for SKU s by customer c in period t (pallets)

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