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The activity-based aggregate production planning with capacity expansion in manufacturing systems

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ABSTRACT

This paper builds a mixed integer linear programming (MILP) model to mathematically characterize the problem of aggregate production planning (APP) with capacity expansion in a manufacturing system including multiple activity centers. We use the heuristic based on *capacity shifting* with linear relaxation to solve the model. Two linear relaxations, i.e., a complete linear relaxation (*CLR*) on all the integer variables and a partial linear relaxation (*PLR*) on part of the integer variables are investigated and compared in computational experiments. The computational results show that the heuristic based on the *capacity shifting* with *CLR* is very fast but yields low-quality solution whereas the *capacity shifting* with *PLR* provides high-quality solutions but at the cost of considerable computational time. As a result, we develop a hybrid heuristic combining beam search with *capacity shifting*, which is capable of producing a high-quality solution within reasonable computational time. The computational experiment on large-scale problems suggests that when solving a practical activity-based APP model with capacity expansion at the industrial level, the *capacity shifting* with *CLR* is preferable, and the beam search heuristic could be subsequently utilized as an alternative if the relaxation gap is larger than the acceptable deviation.

1. Introduction

Aggregate production planning (APP) is used to determine optimal production and inventory levels to meet the demand for all products over a finite planning horizon with limitations of capacities or resources (Graves, 2002; Nam & Logendran, 1992). As a planning task at upper level in hierarchical planning systems, APP is usually made at an aggregate level, where all products are grouped into several aggregated items and the model is often a linear optimization problem. Although some production plans are integrated with lot-sizing and scheduling problems (Gelders & Van Wassenhove, 1981), APP seldom considers the limitation of the detailed planning problem and focuses instead on relevant long-term factors (Axsäter, 1986), typically the monthly or quarterly demand and the production of aggregated items.

Most APP models assume that production capacity remains unchanged and seldom concern themselves with capacity planning issues. However, capacity changes often take place in practical production systems and therefore lead to the capacity expansion problem. Since Manne (1961) proposed the first model for the capacity expansion problem, this topic has been extensively studied in recent decades (Julka, Baines, Tjahjono, Lendermann, & Vitanov, 2007; Rajagopalan, 1998). Examples can be found in the automobile industry (Eppen, Kipp, & Schrage, 1989), communication networks (Gendreau, Potvin, Smires, & Soriano, 2006), the chemical industry (Ahmed & Sahinidis, 2000; Liu & Sahinidis, 1995, 1997), the semiconductor industry (Chou, Cheng, Yang, & Liang, 2007), etc.

Capacity expansion models mainly consider capacity adjustment and do not focus their attention on resource allocation, product mix, and inventory level, which are often the concern of production plans. As a strategic-level plan, a capacity expansion decision cannot be used directly as an instruction for the medium-term APP. As a result, quite a few studies combine the aggregate production planning problem with the issue of capacity expansion (Rajagopalan & Swaminathan, 2001; Van Mieghem, 2003). Bradley and Arntzen (1999) proposed an APP model to make a tradeoff between inventory level and capacity expansion in a multi-stage manufacturing system. Their model does not require that products be aggregated but assumes that capacity scenarios are predetermined. Rajagopalan and Swaminathan (2001) proposed a coordinated production planning model to optimize capacity expansion, production planning, lot-sizing and inventory management simultaneously. In their model, the production system is modeled as a single-stage production line. Atamtürk and Hochbaum (2001) presented capacity acquisition models consider-

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ing subcontract, production, and inventory to satisfy non-stationary deterministic demand over a finite horizon. Generally, the model of production planning with capacity expansion focuses on either the capacity adjustment or the allocation of the changeable resources to production activities with the aim of yielding products that satisfy customer demand. This builds a better connection between the capacity investment at strategic level and the production plans at operational level.

However, most of the existing models of APP with capacity expansion do not take into account product structure or manufacturing processes. Moreover, they restrict themselves to a single-product environment or a one-stage case, and they frequently assume that all items have been transferred to equivalent final products without consideration of inventory, semi-manufactured products, or work in process (WIP). However, this is not applicable to multi-stage production systems where multi-level structures of products and production processes should be considered.

With the development of manufacturing technologies and analytical methods such as activity-based costing (ABC) (Cooper & Kaplan, 1988; Gupta & Galloway, 2003) and cellular manufacturing (Balakrishnan & Cheng, 2007), several production planning models have considered production processes based on the production network of activity centers. Malik and Sullivan (1995) developed a mixed integer programming model that utilizes ABC information to determine the optimal product mix without the assumption of a known unit cost for each product before solving the product mix problem. Schneeweiss (1998) presented a general production-investment problem based on ABC and evaluated the applicability of ABC as a planning instrument. Shapiro (1999) built a comprehensive model that uses ABC and mathematical programming to determine strategic resource planning including facility opening and activity operation level. Kee and Schmidt (2000) modeled the selection of production-mix with the capacity constraints of production-related activities integrating ABC. Singer and Donoso (2006) developed a model to assess the feasibility of prospective production plans. In the model, the unit product cost is calculated through ABC and the production system is regarded as a network of activities connected by physical flows.

The above studies show that under the ABC system, the APP model can optimize product mix policy for final products and semi-manufactured products simultaneously, with manufacturing processes, activity capacity constraint, and product structure considered. Similarly, all of these factors can also be integrated in APP with capacity expansion if we regard activity centers as manufacturing nodes whose capacity is expanded. A few studies on this topic can be found in the literature. Tsai and Lin (2004) and Tsai and Lai (2007) developed ABC-based product mix decision models incorporating capacity expansion, where process-level activity costs are assumed as the stepwise fixed cost and the costs of facility-level activities as the common fixed cost. Kee (2008) examined the usefulness of product and variable costs for pricing, product mix, and capacity expansion taking into consideration economies of scope in an ABC system. These models did not consider the product structure or semi-manufactured items because they are based on the ABC accounting system, not on production process systems. Gupta (2001) pointed out that a process map, i.e., a product-process structure, can be constructed to show graphically the relationship of each activity to the products if a process-oriented activity-based management system is developed. Zhang and Wang (2009) proposed a scenario-based stochastic capacity planning model taking account of product structure, production and inventory levels, and activity processes. However, they did not consider fixed costs of capacity expansion and an algorithm for solving their model has not been developed.

In this study, we first formulate an MILP model for the problem of APP with capacity expansion in a manufacturing system with multiple activity centers, and then develop an effective approach to solving the proposed model. In the model formulation, the product configuration and the physical production flows among activity nodes are brought together, which provides a tool that supports decision makers in considering the product-process structure when determining APP plan with capacity expansion. Moreover, we divide the investment cost for expanding capacities into two parts: fixed cost and variable cost, and we constrain the amount of expanded capacity to be an integer multiple of one unit of activity cell. Next, we investigate the *capacity shifting* approach with linear relaxation for the solution. A computational study shows that in some cases, the *capacity shifting* with *complete linear relaxation* (*CLR*) on all the integer variables does not always result in a high-quality solution because the relaxation does not yield a tight lower bound. Therefore, we consider relaxing only part of the integer constraints, called *partial linear relaxation* (*PLR*), to yield a tight lower bound albeit at the cost of much greater computational time. Finally, we develop a hybrid heuristic by combining *capacity shifting* with beam search for solving the *PLR* of large-scale problems. Computational experiments show that the hybrid heuristic can yield very high-quality solutions within acceptable CPU time.

The rest of the paper is organized as follows. In Section 2, we describe the manufacturing system with multiple activity centers and build the model of activity-based APP with capacity expansion. Section 3 briefly explains the basic framework of the beam search algorithm. In Section 4, the detailed heuristics are introduced, including the *capacity shifting* with LP relaxation and the hybrid heuristic combining the *capacity shifting* approach with the beam search algorithm. In Section 5, computational experiments are conducted to evaluate the performances of the proposed heuristics. In the final section, we present some conclusions.

2. Activity-based APP with capacity expansion

2.1. Activity-based manufacturing systems

Following Singer and Donoso (2006), a manufacturing system can be regarded as a network of activity nodes, renamed *activity centers* in this paper. An activity center produces items (products, semi-manufactured products, parts and accessories) through performing one specific type of activity, e.g., lathing activity, milling activity, or setup activity, etc. As in Bradley and Arntzen (1999), we focus on the assets and costs at manufacturing level that are directly attributable to performing production activities. Furthermore, we assume that the entire cost of resources consumed by activities has been allocated to activity centers using the ABC system. As a result, the variable cost of production comes from the activities performed by the activity centers.

Consider a manufacturing system including N activity centers and M items produced. We assume that each final product is decomposed by means of the bill of materials (BOM) and the work breakdown structure (WBS) into semi-products, parts, or accessories until each item can be manufactured only in one activity center. The serial number of the activity center is denoted by k ($k = 1, \ldots, N$) and the index of items is denoted by i ($i = 1, \ldots, M$). *Let* $\kappa(i)$, $\kappa(i) \in \{1, \ldots, N\}$ *denote the serial number of the activity center that produces item i, and* $I(k) \in \{1, \ldots, M\}$ *denote the set of items manufactured in activity center k.* Considering the multi-level product structure, if an item is a part or a material, it will be used for manufacturing other items, and if it is a final product, it will be sold to customers. Therefore, an item can always be used to meet demand in its downstream activity centers or in the market. Fig. 1 depicts a production network constructed by activity centers (*AC* for short).