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Mixed integer linear programming formulation for flexibility instruments in capacity planning problems

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ABSTRACT

We present a mixed integer linear programming (MILP) approach for an aggregate production planning (APP) problem of an electronics manufacturer. A multi-item, multi-facility, multi-stage capacity planning problem over a finite planning horizon with deterministic demand is considered. We include the flexibility instruments shift planning, overtime account, and flexible maintenance. We present an extensive computational study where the proposed model is applied in a real-world case study and for randomly generated instances. Using a full factorial experimental design we evaluate the cost saving potentials of the flexibility instruments and their combinations. The computational efficiency of the proposed model formulation is investigated by different MILP solvers.

1. Introduction

Nowadays, manufacturing companies have to cope with an increasing demand variation due to shortening product life cycles and seasonality. Demand variation stipulates increasing flexibility in the production environment. Aggregate production planning (APP) provides this flexibility by adapting the internal resources to the demand variations. APP determines optimal levels of production, inventory, and workforce over a given finite planning horizon by taking restrictions on the demand fulfilment and production resources into account. Therefore, effective and flexible production planning can be essential for the success of a manufacturer in highly competitive manufacturing environments.

Our work was motivated by a highly automated electronics manufacturer who produces multiple items at several facilities with different costs in multi-stage production processes with parallel machines and capacity limitations over multiple periods with time-varying future demand forecasts. The manufacturer faces significant demand variations over the planning horizon. The main challenge is to optimise and balance resource utilisations on different production lines. To do so, we introduce a mathematical model formulation that integrates three flexibility instruments into the APP: Flexible shift planning, overtime account, and flexible maintenance.

Flexible shift planning and overtime account are two important flexibility strategies in APP that help manufacturers to adapt supply capacities. Shift planning includes several shift models, each associated with a predetermined shift cost calculated mainly through the required workforce level. Hence, the manufacturer may benefit from flexible shift planning by adapting the workforce level to demand variations. Switching between shift models, however, requires an adaptation of the workforce level, which results in extra cost. In this work, we do not explicitly consider detailed staff planning. Instead, we use flexible shift planning to adapt working time and consequently the workforce level. This aggregation of workforce planning into flexible shift planning makes sense in highly automated manufacturing environments – like the company under study in this paper – where production characteristics such as the cycle times are not heavily influenced by the workforce level.

In contrast to the typical working time account, which accumulates the differences between the actual working hours and the working hours in the contracts, we introduce an overtime account that captures the interrelation between regular working time and overtime. This flexibility enables the manufacturer to compensate under-time hours with overtime hours and to minimise the total overtime cost with respect to the regulations and collective agreements.

Additionally, integrating flexible maintenance into APP may also be beneficial for the manufacturer, since it allows for optimal scheduling of interval-based maintenance activities. This integra-

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tion also minimises the interruption of the production activities due to maintenance when production resources are highly utilised in peak times.

Our contribution is a practical application of capacity planning models based on a real-world problem in the highly automated electronics industry. To gain managerial insights into the value of the different flexibility instruments in APP, we implement a full factorial experimental design by defining input factors like the available production capacity, demand variation, shift cost, and shift change cost. For practical purposes, we analyse the computational performance of the proposed model, using both commercial and non-commercial solvers. Specifically, we address the following research questions: (1) What is the cost benefit of applying the flexibility instruments in a highly automated manufacturing environment separately or in combination with each other? (2) How robust is the proposed mathematical model formulation in terms of solving the underlying problem under different input factor levels using different MIP solvers?

The remainder of this paper is structured as follows. Relevant literature is reviewed in Section 2. Section 3 describes the problem and the flexibility instruments and Section 4 presents the mathematical formulation of the problem. Section 5 presents an extensive numerical study. Finally, Section 6 summarises the findings of the paper.

2. Literature

Different models and solution approaches have been developed for APP over the last decades. An extensive review is given by Nam and Logendran (1992). There are two streams of literature relevant to this work. First, we review the most relevant literature dealing with capacity adaptation and workforce planning with or without overtime account. Then, we review relevant literature dealing with the integration of maintenance into APP.

Silva, Lisboa, and Huang (2000) studied an aggregate production planning model where the workforce level can be adjusted at the beginning of the planning horizon and remains unchanged afterwards. Lagodimos and Mihiotis (2006) studied shift planning with overtime accounts. Their results show that an effective use of overtime leads to workforce reductions and improved utilisation. Da Silva, Figueira, Lisboa, and Barman (2006) developed a multi-criteria MILP model (maximizing profit, minimizing late orders, minimizing changes of the workforce level) by taking constraints of production, inventory and workforce into account. They embedded the developed model into a decision support system for practical usage. Othman, Bhuiyan, and Gouw (2012) developed a multi-objective non-linear programming model to determine the workforce level and overtime hours. Ramezanian, Rahmani, and Barzinpour (2012) introduced a MILP model for an aggregate two-stage production planning problem and applied a genetic algorithm and tabu search to solve the problem. Askar and Zimmermann (2007) and Askar, Sillekens, Suhl, and Zimmermann (2007) addressed a capacity adaptation and staff planning problem on a single assembly line in the automotive industry by taking cycle time, shift planning, work regulations, and line balancing into account. They proposed a solution approach based on dynamic programming and showed that some real world problems can be solved efficiently. Sillekens (2008) and Sillekens, Koberstein, and Suhl (2011) introduced a MILP version of the problem studied by Askar and Zimmermann (2007) extending it to include buffers between shops. Walter, Sommer-Dittrich, and Zimmermann (2011) evaluated volume flexibility instruments using a three-step method that consists of a preliminary analysis where the effective flexibility instruments are identified, an optimisation model, and design-of-experiments techniques for evaluating the flexibility instruments. Hemig, Rieck, and Zimmermann (2014) discussed an integrated production and staff planning problem for heterogeneous, parallel assembly lines in the automotive industry, proposing a dynamic programming solution approach. Merzifonluoğlu, Geunes, and Romeijn (2007) developed a class of production planning models integrating subcontracting and overtime options. They provide effective solution methods using polyhedral properties and dynamic programming techniques.

Another area of research relevant to our work is the integration of maintenance planning into aggregate production planning. Typically, production planning and maintenance planning are considered separately. While production planning models try to balance the total costs of production and inventory, maintenance planning models usually aim at balancing the costs and benefits of maintenance in order to ensure a reliable production system. The two goals might sometimes contradict each other (Aghezzaf, Jamali, & Ait-Kadi, 2007). Hence, only a few papers address the integration of maintenance and APP. Weinstein and Chung (1999) proposed a three-stage model for evaluating maintenance policies of an organisation by integrating the model into APP. First, they generated an aggregate production plan. Then a master production schedule that minimises the deviations from the specified first-stage aggregate production goals was developed. Finally, they used work centre loading requirements to simulate equipment failures during the planning horizon.

Aghezzaf et al. (2007) discussed a joint production and maintenance planning model for a production system, including random failures for finding an integrated lot-sizing and preventive maintenance strategy. Najid, Alaoui-Selsouli, and Mohafid (2011) considered a joint production and maintenance problem and presented a MILP that takes demand shortages and reliability of the production line into account. Their model can be solved to optimality for small problems. Allaoui, Castagliola, Pellerin, Sitompul, and Aghezzaf (2011) propose two-level planning to hierarchically integrate production and maintenance planning. They integrated preventive maintenance into APP and corrective maintenance in the detailed planning. Alaoui-Selsouli, Mohafid, and Najid (2012) incorporated a Lagrangian relaxation heuristic for solving a joint production planning and maintenance problem. Arts and Flapper (2015) introduced a MILP model for an aggregate planning of rotable overhaul and supply chain operations to determine aggregate workforce levels, turn-around-stock levels of modules, and overhaul and replacement quantities per period.

Our paper is based on Lingitz, Morawetz, Tavaghof-Gigloo, Minner, and Sihn (2013), where a cost modelling approach integrating flexible shift planning and overtime account, is presented. In this paper, we also integrate flexible maintenance into APP and discuss the value of each flexibility instrument to highlight the benefits of an increased flexibility for the manufacturer. We also conduct an extensive numerical study to show the applicability of our model for practical purposes by solving it with commercial and non-commercial solver. In contrast to Lingitz et al. (2013), (1) we additionally integrate flexible maintenance to shift planning and an overtime account into APP and discuss the impact of different flexibility levels on costs to highlight the benefits of an increased flexibility for the manufacturer, (2) we conduct an extensive numerical study and present a full factorial design based on randomly generated data to analyse different scenarios, (3) we show the applicability of the proposed model for practical purposes by solving it with commercial and non-commercial solvers.