Data-Driven Decision Making for Strategic Production Planning in a Brewing Company

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Abstract. Changing consumer preferences present a difficult challenge to the brewing industry and hence necessitate adaptations of the production system due to changed requirements. Beer manufacturing is subject to restrictive dependencies, such as lead times, shelf life, multilevel processes, and storage tank restrictions. Therefore, we propose a multilevel capacitated lot-sizing problem (MLCLSP) that covers brewery-specific constraints. The investigated brewing company produces 220 finished and 100 semifinished products on 13 production and 8 storage resources within 3 production levels. Since the brewery-specific MLCLSP cannot be solved within reasonable computing time in the case at issue, we introduce a priority-based fix-and-relax-and-optimize heuristic. We present a computational study and managerial insights regarding changes in consumer preferences (i.e., additional products with low demand). We prove that the priority-based strategy dominates the standard strategy in solution quality and computation time. Furthermore, we demonstrate the potential of the MLCLSP-based planning approach for strategic decision making by revealing the impact on the entire production system.

Keywords: Strategic planning and management · Production and inventory systems · Decision support systems

1 Introduction

Strategic planning of complex production systems is difficult but of great importance for the brewing industry because of fast-changing consumer preferences. Recently, consumers demand individual (i.e., innovative and unique) beers which result in additional products with low demand. However, large breweries are designed for high production volumes and hence require adaptations. Most material requirement planning (MRP) tools within an enterprise resource planning (ERP) system do not support strategic decision making. Therefore, we propose a multilevel capacitated lot-sizing problem (MLCLSP) that covers brewery-specific constraints. Since the proposed mathematical program cannot be solved within reasonable computing time in the case at issue (i.e., 220 finished products, 100

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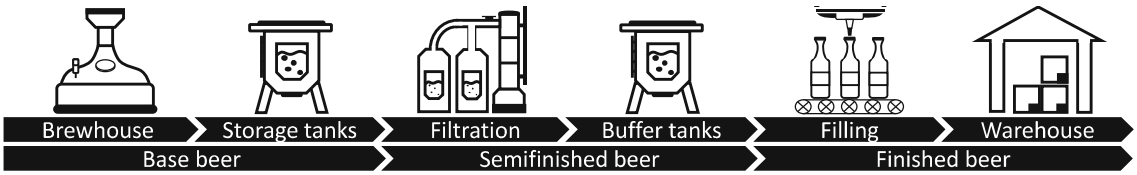

Fig. 1. Production process of a brewery

semifinished products, 13 production resources, 8 storage resources, 3 production levels, and 52 weeks within the planning horizon), we introduce a priority-based fix-and-relax-and-optimize (FRO) heuristic. The priority-based approach first determines a basic production schedule for priority products and then supplements it with secondary products. In this study, we investigate necessary adaptations of the production system due to changed consumer preferences. Furthermore, we demonstrate computational benefits of the priority-based solution strategy for the FRO heuristic.

Figure 1 shows the brewery production process from base beer to finished beer. The brewhouse brews the base beer. The fermentation and maturation processes stay at least two weeks in the storage tanks. Next, the filtration removes yeast and other particles from the base beer. Different recipes (e.g., mixing ratios) result in several types of beer. Before filling, buffer tanks temporarily store the semifinished beer. Finally, the warehouse stores the finished beer.

The MLCLSP has been extensively studied in the literature. However, only a few studies address the brewery production planning problem. Förster et al. [1] propose a capacitated lot-sizing problem that considers availability constraints of reusable bottles in a brewing company. Baldo et al. [2] adopt the synchronized and integrated two-level lot-sizing and scheduling problem (SITLSP) to the brewing industry. Both studies focus on operational and tactical issues. In contrast, our model approach supports strategic decision making, hence the periods are weeks instead of days or hours.

2 Brewery-Specific MLCLSP

Problem Statement

The proposed MLCLSP is based on the general formulation by [3] and the brewery-specific extension by [4]. We take into account limited production and storage capacity but allow the use of overtime and external warehousing. Each product is allocated to one production and one storage resource. We aggregate identical storage tanks to tank groups but assign each liquid to an individual tank. The model takes into account lead times for fermentation and maturation. The maximum permissible duration of advance production of semi-finished beer is one week. We consider setup losses and assume setup times to be sequence-independent. The model considers an initial and final inventory to guarantee the production capability at the beginning of and beyond the planning horizon. Base beer requires production in discrete batch sizes. Furthermore, demand fluctuations necessitate to hold a safety stock to meet service level agreements. To avoid spoilage of perishable goods, we consider the shelf life of finished beers.

Table 1. Set and parameter notation used for the brewery-specific MLCLSP

Indices and index sets		**Parameters**	
$\mathcal{I}, \mathcal{J}$	Set of products with index i, j	b_i	Batch size of product i, for $i \in \mathcal{B}$
$\mathcal{B}$	Subset of base beer products, $\mathcal{B} \subset \mathcal{I}$	$c_{t,r}$	Capacity of resource r in period t
$\mathcal{S}$	Subset of semifinished beer products, $\mathcal{S} \subset \mathcal{I}$	$d_{t,i}$	Demand of product i in period t
$\mathcal{R}$	Set of resources with index r	f_i	Production time for product i
$\mathcal{M}$	Subset of production resources, $\mathcal{M} \subset \mathcal{R}$	g_i	Setup time for product i
$\mathcal{N}$	Subset of storage resources, $\mathcal{N} \subset \mathcal{R}$	h_i	Holding cost of product i
$\mathcal{H}$	Subset of tank groups, $\mathcal{H} \subset \mathcal{N}$	$k_{t,i}$	Given safety stock level of product i in period t
$\mathcal{T}$	Set of periods with index t	$l_{t,i}$	Permitted minimum production quantity of product i in period t
$\mathcal{I}_r$	Set of products i assigned to resource r	$m_{t,i}$	Given demand within shelf life of product i in period t
$\mathcal{J}_i$	Set of products j that are direct successors of product i	n_r	Number of tanks within tank group r, for $r \in \mathcal{H}$
		o_r	Overapacity cost of resource r
		$p_{i,j}$	Quantity of product i required to produce product j
		s_i	Setup cost of product i
		$u_{t,i}$	Permitted maximum production quantity of product i in period t
		v_i	Specific tank volume of product i (depending on assigned tank group)
		w_i	Setup loss of product i

Model Formulation

The mathematical program optimizes inventories $I_{t,i}$, lot-sizes $Q_{t,i}$, and setups $X_{t,i}$ for each period t and product i. In addition, the model determines discrete batch sizes $M_{t,i}$ and the number of used storage tanks $N_{t,i}$ for each period t and base beer product $i \in \mathcal{B}$. Besides, the model calculates the overcapacity $O_{t,r}$ for each period t and resource r. Table 1 lists the used set and parameter notation.

$$\min F = \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} h_i \cdot I_{t,i} + \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} s_i \cdot X_{t,i} + \sum_{t \in \mathcal{T}} \sum_{r \in \mathcal{R}} o_r \cdot O_{t,r} \tag{1}$$

s.t.

$$I_{t-1,i} + Q_{t-\lambda_i,i} - \sum_{j \in \mathcal{J}_i} (p_{i,j} \cdot Q_{t,j} + w_j \cdot X_{t,j}) - d_{t,i} = I_{t,i} \qquad \forall i, t \tag{2}$$

$$I_{0,i} \leq I_{T,i} \qquad \forall i \tag{3}$$

$$I_{t,i} \leq Q_{t,i} \qquad \forall i \in \mathcal{S}, t \tag{4}$$

$$Q_{t,i} = b_i \cdot M_{t,i} \qquad \forall i \in \mathcal{B}, t \tag{5}$$

$$Q_{t,i} \leq u_{t,i} \cdot X_{t,i} \qquad \forall i, t \qquad (6)$$

$$Q_{t,i} \geq l_{t,i} \cdot X_{t,i} \qquad \forall i, t \qquad (7)$$

$$I_{t,i} \leq v_i \cdot N_{t,i} \qquad \forall i \in \mathcal{B}, t \qquad (8)$$

$$\sum_{i \in \mathcal{I}_r} N_{t,i} \leq n_r \qquad \forall r \in \mathcal{H}, t \qquad (9)$$

$$\sum_{i \in \mathcal{I}_r} I_{t,i} \leq c_{t,r} + O_{t,r} \qquad \forall r \in \mathcal{N}, t \qquad (10)$$

$$\sum_{i \in \mathcal{I}_r} (f_i \cdot Q_{t,i} + g_i \cdot X_{t,i}) \leq c_{t,r} + O_{t,r} \qquad \forall r \in \mathcal{M}, t \qquad (11)$$

$$I_{t,i} \in [k_{t,i}, m_{t,i}] \qquad \forall i, t \qquad (12)$$

$$X_{t,i} \in \{0, 1\} \qquad \forall i, t \qquad (13)$$

$$O_{t,r}, Q_{t,i} \geq 0 \qquad \forall r, i, t \qquad (14)$$

$$M_{t,i}, N_{t,i} \in \mathbb{N} \qquad \forall i \in \mathcal{B}, t \qquad (15)$$

The objective function (1) minimizes the inventory, setup, and overcapacity costs. The inventory balance (2) requires the fulfillment of the demand in each period from stock or actual production. The lead time λ_i takes into account the fermentation and maturation for base beer. The cycle condition (3) requires to produce the quantity demanded within the planning horizon. Equation (4) ensures a maximum permitted advance production quantity of semifinished products. Equation (5) considers the production of base beer in discrete batch sizes. Equation (6) ensures the setup condition. Equation (7) respects minimum lot sizes. Equations (8) and (9) take the storage tank restrictions into account; (8) determines the required number of tanks, and (9) respects the available number of tanks. The storage capacity constraint (10) considers the limited storage capacity and allows external warehousing. The production capacity constraint (11) includes the production and setup time and allows the use of worker overtime. The variable declaration (12) defines a minimum and maximum inventory level by a given safety stock and demand within shelf life.

3 Priority-Based Fix-and-Relax-and-Optimize Heuristic

To solve the brewery-specific MLCLSP within reasonable computing time, we introduce the priority-based FRO heuristic. First, the fix-and-relax (FR) heuristic generates an initial solution and, second, the fix-and-optimize (FO) heuristic improves this solution [5]. Each subproblem of the FR heuristic considers the integer condition for a small part of integer variables while neglecting the integer condition for the remaining variables [6]. The FO approach decomposes the main problem into smaller subproblems with fewer integer variables to be optimized while fixing the previous solution of the remaining variables [7].

The priority-based solution strategy contains two phases. The first phase determines a basic production schedule for prioritized products. The second

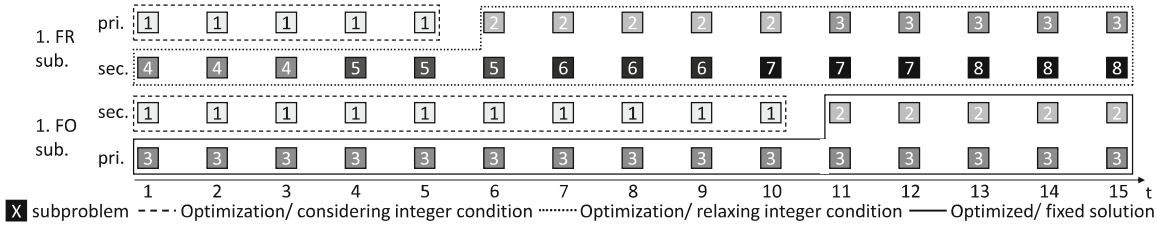

Fig. 2. Procedure of the priority-based FRO heuristic

phase adds secondary products to this basic production schedule. Thereby, we define products with relatively high demand as priority products. Figure 2 shows the procedure of the priority-based FRO heuristic. The first FR subproblem includes the periods one to five of the priority products. The variables within this subproblem consider the integer condition while the remaining variables are relaxed. The first FO subproblem includes the periods one to ten of the secondary products. The variables within this subproblem are optimized again while the remaining variables are fixed. As soon as each subproblem is optimized once, the procedure ends. The given numerical example contains eight FR and three FO subproblems. The priority-based solution strategy also applies to related problems in which attributes can be prioritized.

4 Computational Study and Managerial Insights

We implement the mathematical program and solution approach in GAMS/ CPLEX (v32.1/ v12.10) running on a CPU with 64 cores (4.4 GHz) and 256 GB of RAM.

We investigate the expected consumer preferences represented by four portfolio scenarios. The scenarios differ in additional products (AP) and relative share of additional demand (AD), e.g., in the first scenario, ten additional products lead to an increase in total demand of one percent. Table 2 displays the objective values and computing times depending on the portfolio scenario and solution strategy of the FRO heuristic (i.e., priority-based and standard). The

Table 2. Objective values and computing times depending on the portfolio scenario and solution strategy

Scenario	Parameter	Results (priority strategy)		Results (standard strategy)	
	AP/AD	Obj. v. (T€)	Com. t. (s.)	Obj. v. (T€)	Com. t. (s.)
#0		2,871	975	3,108	932
#1	10/1%	3,495	1,180	3,387	1,236
#2	20/1%	3,726	1,544	3,941	1,690
#3	10/5%	4,125	1,437	4,173	1,740
#4	20/5%	5,978	1,600	5,918	2,154

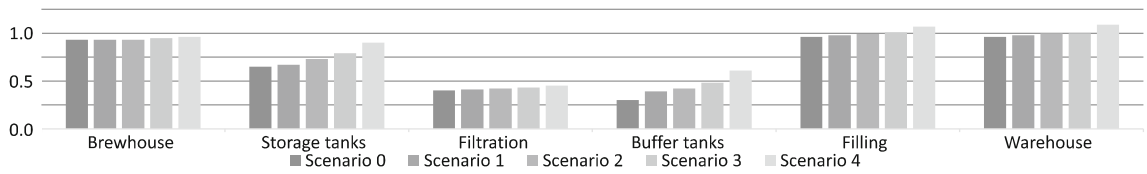

Fig. 3. Capacity utilization for each resource within the multilevel production system

priority-based solution strategy achieved lower costs and computing times compared to the standard solution strategy (i.e., time and product decomposition). Thereby, greater resource scarcity increases the computing time. However, additional demand has a greater impact than additional products. Moreover, the portfolio scenario 4 exhibits the highest costs due to an intensive use of overcapacity.

Figure 3 shows the capacity utilization for each resource within the multilevel production system. The expected consumer preferences affect the entire production system, especially the tank resources due to specific restrictions, e.g., single occupancy. Portfolio scenarios 1 to 3 do not necessitate adaptations of the production system. Therefore, we recommend to introduce those portfolios under consideration of the additional operating costs. However, portfolio scenario 4 exceeds the available capacity of the filling line and warehouse. Nevertheless, this scenario is feasible with acceptance of worker overtime and external warehousing.

5 Conclusion

In this study, we propose a brewery-specific MLCLSP and a priority-based FRO heuristic. We demonstrate that the priority-based strategy dominates the standard strategy in solution quality and computation time. Furthermore, we show that the MLCLSP-based planning approach supports strategic decision making by revealing the impact on the entire production system. The results highlight the importance of multilevel planning to avoid inefficient investments.

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