Integrated production planning, shift planning and detailed scheduling in a tissue paper manufacturer

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Abstract—**In this paper, we report an integrated planning system we developed for a large tissue paper manufacturer in Turkey. The system is composed of three integrated models to solve the capacity planning, shift planning and scheduling problems. All three problems are solved by an intelligent mix of optimization methods and heuristics.**

We also report the implementation process of the system in the manufacturing company, and discuss observed benefits of the system in terms of the competitive position of the company.

Index Terms—**Capacity planning, scheduling, shift planning, mixed-integer programming.**

I. Introduction

In this study we develop an integrated planning system in the largest tissue paper manufacturing company in Turkey. Production process of the company is composed of two major phases: paper production, where tissue paper is produced in bulk quantities, and converting, where large paper rolls are cut into size and packaged.

In the system that we model, paper is produced in one plant. After the bulk paper is obtained, it can either be sold directly to customers as bulk tissue paper, or it can be converted to any one of the possible end products, such as bath tissue, paper towels and napkins. The organization of the multi-facility manufacturing system is given in Figure 1. The main converting facility is adjacent to the paper production plant. There is a second converting facility owned by the company in a different region in Turkey. The company also works with two contractors with converting facilities in different geographical locations.

The competitive strength of the company (in terms of manufacturing strategy) depends on the better management of the following factors:

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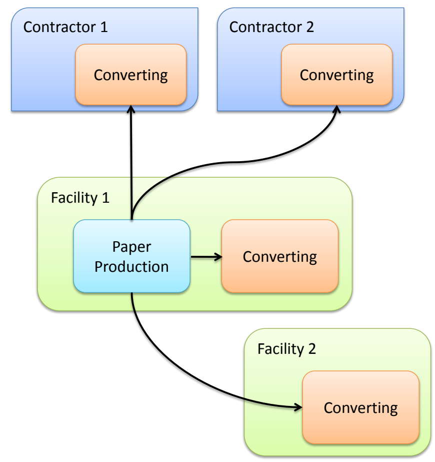

Fig. 1. Manufacturing organization of the company

- End products are produced to inventory. The company needs to have a proper mix of inventories in the face of changing market dynamics.
- Since tissue paper production is performed on large dedicated machines, capacity installed for the paper production phase is considerably larger than the requirements of the converting facilities. Hence, the company needs to balance the possibility of selling the bulk paper as a product and the internal demand generated by the converting facilities.
- The company operates in a very dynamic market, and needs to respond to changes in the market rapidly without compromising operational integrity.
- Profit margins of the sector are relatively limited, and the company must keep its operational costs as low as possible.

Architecture of the integrated planning system that we developed is shown in Figure 2. The planning system includes three integrated modules: capacity planning (CPM), shift planning (SPM) and scheduling (SM). In the company, there are three

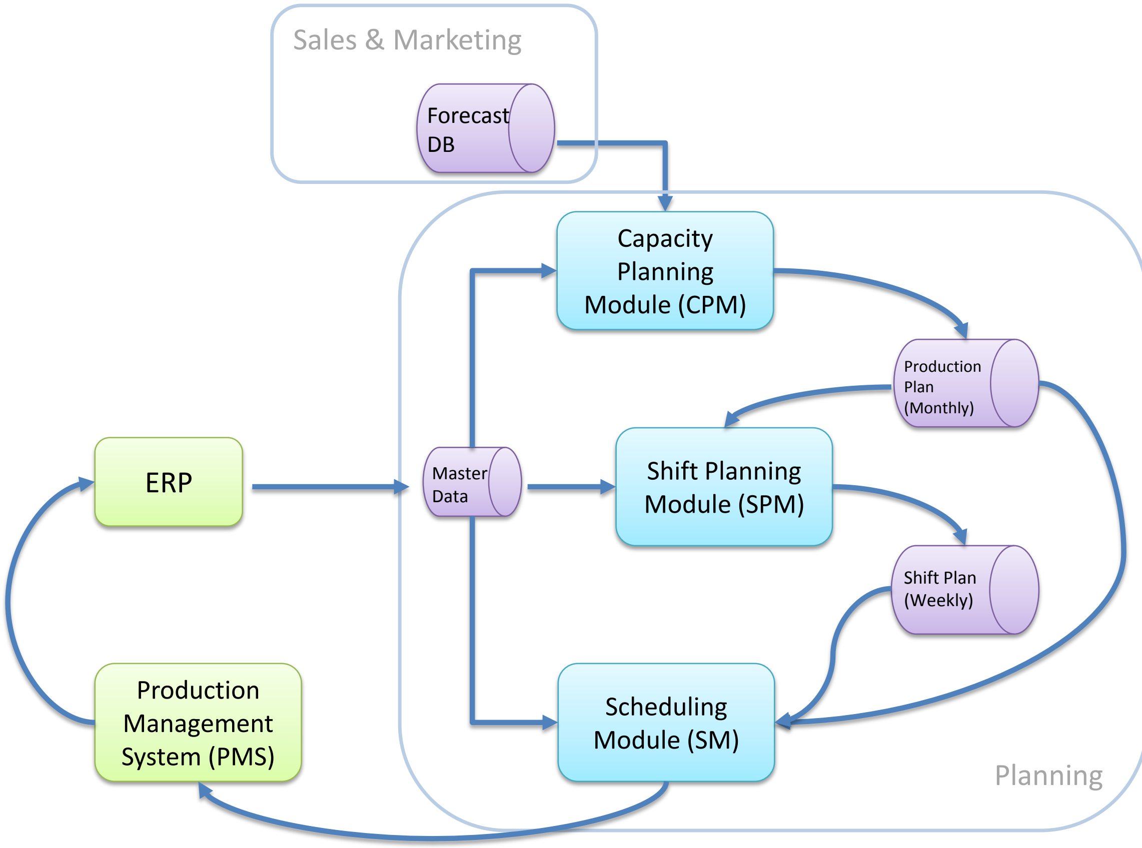

Fig. 2. Integrated planning system architecture

major operation processes that our planning systems interacts with:

- **Forecasting:** Demand forecasts are generated by the Sales & Marketing Department (SMD) on a monthly basis. Within the month, forecasts may be updated jointly by the SMD and the Planning Department, through continuous evaluation of current market conditions, competitor actions and realized sales.
- **ERP:** Most of the data needed by our planning system is maintained in the Enterprise Resource Planning (ERP) system used by the company. The master data maintained by the ERP system consists of product and raw material definitions and inventory levels, production resource and routing definitions, bill of materials, open production orders, customer orders and requested deliveries.
- **Shop floor control:** On-line shop floor control is managed on the company's Production Management System (PMS). PMS collects data about production realizations and machine breakdowns from the shop floor and feeds the ERP system.

The three main components of our planning system perform the following tasks in conjunction with these external processes:

- **Capacity Planning Module (CPM)** generates a monthly production plan for the medium-term planning horizon, which typically consists of the next four months. The generated plan optimizes inventory flow both within the company's facilities and its contractors by explicitly considering production capacity, technical constraints of the production processes and manpower availability. CPM uses the forecasts generated by the SMD and retrieves the other required data from the ERP system.
- **Shift Planning Module (SPM)** determines the optimum number of shifts each work center should operate on a weekly basis throughout the planning horizon. SPM explicitly considers

the man-hour requirements determined by the CPM, maintenance schedules and restrictions dictated by the labor law.

- **Scheduling Module (SM)** generates a detailed schedule for the short-term planning horizon, which typically consists of the next two weeks. The generated schedule is based on the net productions requirements (determined by the CPM) and the installed man-hours (determined by the SPM). Generated schedule is released to the PMS to guide the production processes in the shop floor.

Each of the individual problems that we consider has received a significant amount of interest in the literature. We refer the reader to [1] for a comprehensive treatment of production planning using mathematical programming methods. Optimization methods have been used for shift planning in various industries (e.g., [2], [3], [4]) and [5] surveys the use of optimization techniques for solving scheduling problems. Several studies have focused on designing integrated methods for solving production planning and scheduling problems (e.g., [6], [7], [8]). Relatively few researchers have considered the interaction between shift planning and production scheduling ([9], [10]). However, to the best of our knowledge, no prior work that integrates capacity planning, shift planning and scheduling exists in the literature.

We provide the details of three modules of the implemented planning system in Section II. Discussions on implementation results and conclusions are given in Section III. Note that we focus on a high-level overview of the planning system in this paper. The details of our mathematical programming formulations are available in [11].

II. Planning Modules

A. Capacity Planning Module

Capacity Planning Module (CPM) aims to generate an optimal production and contracting plan for the medium-term planning horizon. The CPM is based on a linear programming (LP) model similar to a classical aggregate production planning model given in [1], where we use monthly periods. The main decision variables are:

- monthly production quantities
- monthly material purchase requirements
- inventory levels at the end of each month
- resource usage levels
- amounts of finished and semi-finished goods transferred between facilities
- amount of capacity allocated to external paper demand

Constraints of the model include:

(I1) inventory balance, including semi-finished good transfers between facilities
(I2) minimum ending inventory level
(I3) product family based batching related inventory constraints in the converting phase
(P1) material requirement and availability
(P2) minimum production amount outsourced to contractors
(C1) resource and manpower availability
(C2) excess capacity allocation for possible external paper demand

Constraints (I1), (P1), and (C1) are the classical constraints of the capacitated aggregate planning model. Constraints (I2) allow the planners to reflect their experience on the generated plan, for instance by foreseeing possible future fluctuations on demand, which are not reflected on the official forecasts. Constraints (P2) ensure that the company honors its long-term capacity allocation agreements with its contractors.

Constraints (I3) handle product family based batching issues. Production processes on certain machines in the "converting" stage contains family setups, which are very costly and sequence-dependent. Therefore, products belonging to those families are produced in a sequence determined by the planner and each product family is typically produced at most once in a month. Figure 3 shows an example of this case. Here, A, B, C and D are product families, which are to be produced in the given sequence in periods t and $t+1$.

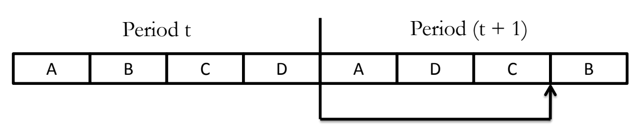

Fig. 3. An example for the production sequence of product families

Consider product family B, which is to be produced as the second batch in period t and as the last batch in period $t+1$. It is easy to see that inventory levels of the products in family B at the end of period t should be able to meet the demand that is expected to realize until the production of product family B starts in period $t+1$. Constraints (I3) model the dynamic minimum inventory requirements originating from product family batching. In our model we assume that demand within a month realizes at a constant rate throughout the period.

CPM utilizes the SPM in modeling the capacity constraints regarding the converting facilities. Currently active shift plan released by the SPM is used as the installed capacity limit in Constraints (C1). The planner also may run our model to allow the possibility to use more capacity than the SPM dictates at a higher cost. If there is additional capacity used in the optimum solution, the SPM is informed of the additional capacity requirements to generate a new shift plan.

In the paper production phase, since the paper machine is very expensive, the system is run 4 shifts (7x24) all the time. Hence the installed capacity in paper production is higher than the required capacity for the operation of the converting facilities. Hence, our model also suggests allocation of the excess capacity to possible external demand for tissue paper. Constraints (C2) model the preferences of the planners in evaluating the paper sales opportunities.

The objective function of our linear programming model minimizes the total cost, which consists of production, purchasing, resource usage, and inventory holding costs.The number of decision variables and constraints are approximately 72.000 and 32.000, respectively. The construction of the optimization model and and its solution process take less than two minutes. Therefore, planners are able run CPM any time an important change in master data occurs, see its impact and react rapidly.

B. Shift Planning Module

Shift Planning Module is responsible for the generation of a shift plan in alignment with the production plan generated by the CPM. The company can operate on various shift plans in accordance with its agreements with the labor union such as 8:00–16:00, 8:00–24:00, 7x24, etc. Each production resource may either be assigned one of the available shift plans throughout the week, or it may be closed for the week.

In the SPM, we solve a mixed-integer programming (MIP) model for each resource. The main decision variable of our model represents the shift plan assigned to the resource for each week. The generated shift plan needs to ensure that:

- required working hours for the machine, which are calculated by the CPM, are satisfied, and
- no drastic changes to the shift assignments in consecutive weeks are allowed.

Subject to these constraints, our model's objective function minimizes the total number of working hours and the total number of shift plan changes in consecutive weeks. Hence, our model generates a smooth shift plan that satisfies the capacity requirements of production resources with minimum working hours.

The SPM is executed at the beginning of each month for all resources. Planners can re-run the SPM for all production resources or a subset of those as needed. The MIP model for a single resource consists around 120 decision variables and 150 constraints. Even though most of the decision variables are integer variables, construction and solution of the model to optimality typically takes less than twenty seconds.

C. Scheduling Module

Scheduling Module (SM) takes the master data, the monthly production plan generated by the CPM and shift plan generated by the SPM to generate a detailed schedule for a short-term planning horizon, which is typically the next two weeks, by using a two-phase scheduling algorithm.

In the first phase of the scheduling algorithm, we solve an optimization model (bath sizing model) to determine the optimum production batch sizes and to select the optimum machine among alternative parallel machines for each batch. The second phase generates a feasible sequence of the resulting batches on the selected machine using a heuristic procedure.

1) Batch Sizing Model: The Batch Sizing Model (BSM) is a mixed-integer programming model that aims to generate a production plan for the short-term planning horizon based on the production plan of the CPM and the sift plan of the SPM. The model is very similar to an aggregate production planning model with some additional binary variables and special constraints. In this model time periods are shortened, e.g. one period usually has a length of 3 days.

Main decision variables of the model are:

- production quantities
- ending inventory levels
- resource usage amounts
- binary assignment variables that indicate whether each finished or semi-finished product is produced in each period
- binary assignment variables that indicate whether products belonging to each product family are produced in each period

The major constraints of the model are:

- inventory balance equations
- resource capacity
- manpower availability
- minimum production lot size
- sequencing constraints for product families

Note that the product families are defined are at a more detailed level compared to CPM. These detailed definitions are needed in SM level since the constraints related with them become relevant in the short term even though they are negligible at CPM level. In particular, one of the product family definitions is related to semi-finished products. As mentioned in section I semi-finished goods, i.e. large rolls of paper, are produced in a continuous process. That is transitions from one paper type to another is realized without interruption between two production batches. Every paper type contains certain chemical compounds that are specific to that type of paper. Since some paper types contain different and incompatible chemical compounds, transition between those paper types have to be prohibited. For this reason, planners group products having similar properties into families and define a set of transition rules, which we are represented by constraints in our model.

The objective of BSM is similar to the one in CPM, i.e. minimizing the total cost of production, resource usage, and inventory holding costs. An additional cost item for this model is the backorder cost and cost of unsatisfied demand. The number of decision variables and constraints are approximately 28.000 and 18.000, respectively. The model looks ahead for one month, that is it takes demand and production decisions made by CPM for a full month into account. However, since we are interested in the detailed schedule of the next two weeks, we relax the binary variables for the last two weeks. Nevertheless, approximately %30 of all decision variables are binary variables and hence the resulting MIP cannot be solved to optimality within a reasonable amount of time. Therefore, we stop the solution process once an optimality gap defined by the planner is reached. Construction of model and the solution process take approximately five minutes.

2) Sequencing of Batches: The BSM assigns production batches to resources for every time period, but it does not sequence the batches assigned to the same time period. After BSM runs and a close-optimal solution is obtained, we execute a heuristic algorithm to sequence the batches within each time period. Our heuristic algorithm is a simple dispatching algorithm with some specified sequencing criteria. The sequencing criteria to be used are specific to the resource and the product family characteristics of the batches that are being sequenced. The sequencing criteria can be summarized as follows:

1) Sequencing rules regarding product family restrictions
2) For finished goods, the level of importance of customer orders and the time of the earliest customer order
3) For semi-finished goods, the time that the product becomes critical for the progress of finished good production
4) For finished goods, the total forecasted quantity

Our sequencing heuristic uses these criteria to determine the sequence of batches to be produced. We then schedule the batches, i.e. calculate starting and ending times of operations in accordance with the determined sequence. This part of SM executes very quickly, and it usually takes a negligible amount of time compared to solving the batch sizing model.

III. Conclusion

In this paper, we provide an overview of the integrated planning system we developed at the largest tissue paper manufacturing company in Turkey. All three modules were implemented using the development environment provided by ICRON Supply Chain Optimization System [12]. The CPM and SPM modules have been in use since July 2010, while the APS module became operational in October 2010.

Observed benefits of using the planning system can be summarized as follows:

- Optimization of inventory flow resulted in an improved inventory mix, hence customer service levels are significantly increased while keeping the total inventory value the same.
- Joint modeling of production phases provided a reliable decision support environment in regards to optimum allocation of paper production capacity between external sales opportunities and internal demand.
- The operating environment of the company is highly competitive. It is not uncommon to face each month a very drastic marketing move by one of the competitors. Usage of the planning system improved the responsiveness of the company to take correct position against such perturbations on the estimated state of the market conditions.
- Integrating the capacity planning with shift planning improved the utilization of resources in the converting plants.

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