Integrated Production Planning, Shift Planning and Detailed Scheduling in a Tissue Paper Manufacturer

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Abstract In this study, we report an integrated planning system that 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 a combination of optimization methods and heuristics. We also report the implementation process of the system in the manufacturing organization, and discuss observed benefits of the system in terms of the competitive position of the company.

1 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.

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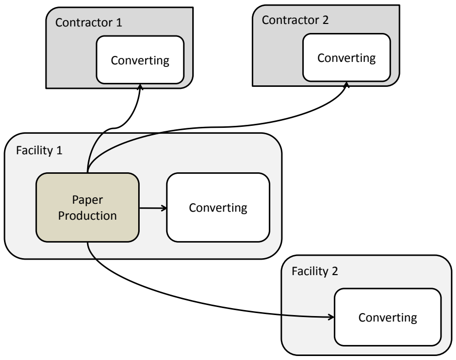

Fig. 1 Manufacturing organization of the company.

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

- 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 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.

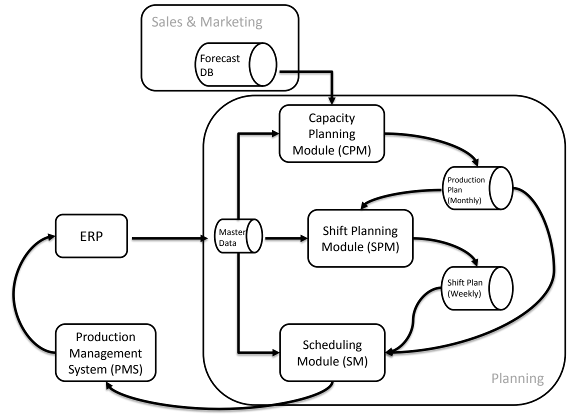

Fig. 2 Integrated planning system architecture.

The modeled planning system has three main components, which 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.

Organization of remaining sections is as follows: Section 2 provides an overview of the literature, where problems in this study are considered. In Section 3, we introduce the characteristics of the competitive environment in which the company is operating. We also give the main characteristics of production environment and mention the performance indicators in planning activities. In Section 4, we define the planning problem as a whole and give definitions of the three individual problems. Section 5 contains descriptions of the three models in detail. In Section 6 we give the details of implementation of the models. The integration of planning system with other systems is also explained in this section. Finally, in Section 7 the implementation results are mentioned.

2 Literature Survey

Each of the individual problems that we consider has received a significant amount of interest in the literature. We refer the reader to [29] for a comprehensive treatment of production planning using mathematical programming methods. Mula *et al.* [27] provide a review of literature in production and transportation planning, where a wide range of mathematical programming methods, such as linear programming, mixed integer programming, non-linear programming, stochastic programming etc., are used in tactical decision level.

In literature, there exist a number of different approaches to different extensions of aggregate production planning problem. Alain [3] and Akartunali *et al.* [2] work on solving mixed integer programming (MIP) formulations of production planning problem, where fixed or setup costs are considered. Fumero [10] and Jolayemi *et al.* [16] consider production planning problem on a network of production plants. Both studies formulate the problem as MIP models.There are studies where lead times are considered in combination with classical aggregate planning approach [17, 35]. Multi-objective approaches also received interest such as goal programming [22] and fuzzy multi-objective linear programming approach [37].

Optimization methods have been used for shift planning in various industries. Ernst *et al.* [9] provide a review of staff scheduling problems of different kinds, application areas and methods. Reader is referred to [5, 8, 14, 19, 20, 36] for some applications in various industries such as food manufacturing, packing, health care and airline, where different approaches are developed to solve shift planning problem.

In our survey we focus on hybrid flow shop scheduling problems where optimization techniques are used. Mendez *et al.* [26] survey the use of optimization techniques for solving scheduling problems. Ruiz *et al.* [33] review studies on hybrid flow shop scheduling problem. In [4], an extensive review on scheduling problems with setup times is provided. In literature, there are studies where real life scheduling problems are solved using MIP models [32, 28, 11, 18]. Developing MIP formulations for variations of scheduling problems has received interest by many researchers (e.g., [7, 34, 13, 30, 25]).

There are studies which combine production planning and planning of labor capacity (e.g., [1]). Several studies have focused on designing integrated methods for solving production planning and scheduling problems (e.g., [21, 23, 24]). Bhatnagar *et al.* [6] mention the problem of integrating aggregate production planning and short-term detailed scheduling decisions, where different decisions are taken in different planning levels. They combine those decisions by proposing a planning scheme with feedback mechanisms among different levels. Xue *et al.* [38] integrate aggregate production planning and sequencing problems in a hierarchical planning system where sequence-dependent family setups exist. Production planning and scheduling problems in a hybrid flow shop are integrated in a decision support system in [31].

Relatively few researchers have considered the interaction between shift planning and production scheduling ([39, 12]). However, to the best of our knowledge, no prior work that integrates capacity planning, shift planning and scheduling exists in the literature.

3 Planning Environment

In this section we provide information about characteristics of competitive environment and the properties of production environment.

3.1 Characteristics of Competitive Environment

The company operates in a highly competitive market where the products are fully substitutable by competitors' products. Through planning activities, the company aims to prevent loss of sales against competitors due to late deliveries and to take proper position against changing market conditions.

Demand reaches through various sales channels to company; wholesale dealers, supermarket chains and export channel. Customers from different sales channels have different business strategies with which the company has to align itself. Wholesale dealers send replenishment orders as soon as their inventory level decreases under a certain level. The magnitude of the order changes by the size of the wholesale dealer. Nevertheless their orders are usually in large quantities. The operation of supermarket chains is different than wholesale dealers in the sense that they do not keep inventory of products. Even if they have a very small inventory located in supermarkets' warehouse and/or shelf, that inventory and also the costs incurred by inventory holding are usually owned by the company. Since supermarkets operate with limited amount of products, they usually generate replenishment orders in small quantities and tight due dates compared to wholesale dealers. The company has to have the ability to satisfy those urgent demands, since the end-consumers have many other choices to buy, if they cannot find company's products on the shelf, which will result in direct loss of sales. Export channel operates based on customer orders from different regions of Europe and Asia. The operation of export channel is very similar to wholesale dealers. The difference is the way they interpret "late" deliveries. Customers out of the country are more prone to cancel orders and also agreements compared to domestic wholesalers when they face disturbances in delivery schedule. The company tries to manage its production and inventory levels to be able to satisfy the demands from different sales channels with different characteristics. The aim here is to keep customer satisfaction at the highest level by decreasing the risk of being stock-out in any product.

The production and inventory management is mostly performed based on forecasts generated by Sales and Marketing department, where they consider all possible factors that might affect the orders originating from different sales channels. Hence, the production mainly follows make-to-stock pattern. Also due to technological and cost-wise limitations, production is performed in large volumes, which leads to high inventory levels and high inventory holding costs. However, the planning department should find a way to keep the inventory levels as low as possible while eliminating the risk of losing sales.

Similar to most commercial institutions, the company aims to increase its profits. This aim is not achievable by controlling the selling prices, since the prices are set by the market. And the profit margins in the sector are highly limited. Hence, in this sector, increasing the profit can only be obtained by decreasing costs such as material acquisition costs, operational costs, i.e. transportation, energy consumption, labor costs, inventory holding costs and setup costs. Since the company does not have any control on the purchasing costs, the operational costs are mainly determining the profit margin. Transportation, process, overhead, inventory holding and setup costs should be lowered through planning activities.

3.2 Characteristics of Production Environment

3.2.1 Two Phase Production

The production process of the company is composed of two major phases: paper production and converting phase. In the first phase, tissue paper is produced in bulk quantities. In the converting phase, bulk papers are “converted” into finished products such as toilet papers, paper towels and tissues.

In the paper production phase, chemical compounds of the paper are mixed in huge containers. The mixture runs through various pipes where it is dried and flattened to the required thickness of paper. The resulting thin paper is coiled up to obtain paper bobbins whose weight differ from 0.5 up to 4 tons depending on the paper type and whose width is approximately 2.5 meters. There are approximately 60 different types of papers, where one paper type can be used in production of several finished products.

Paper production is performed on large dedicated machines, where one paper can be produced in more than one machine. Because of the chemical processes during paper production, product changes on paper machines necessitate significant setups. That is, the remaining chemicals in the large mixing container should be completely removed such that they do not get mixed with the chemicals of the next product, so that the nature of consequent product is not harmed. Those setups require long durations, workforce and high energy consumption.

The second phase is called the “converting” phase. In this phase paper bobbins are loaded on “converting” lines where the paper is cut into required sizes and packaged. Each converting machine is composed of one single line where no interruptions exist between cutting and packaging operations.

There are different types of converting lines. The distinction between converting lines is based on the type of products produced on that line. Converting lines can be divided into four major groups: toilet paper lines, where cylindrical products are produced, tissue lines, napkin lines and facial tissue lines.

3.2.2 Multi-facility Production System

The manufacturing organization of the company is given in Figure 1. The company owns two production plants in different geographical locations. The company has also capacity allocation agreements with two contractors. There are 3 paper machines and 20 converting lines in all production plants.

In the previous section, we mentioned that the paper machines are large dedicated machines. Each of them allocates an area of approximately 20000 m^2. Paper machine installation costs are very high such that they cannot be recovered in a short amount of time. For this reason, among four production plants, paper production is realized only in one plant which is owned by the company. There exists three paper machines operating 7x24 where total production capacity is approximately 87000 tons per year. This installed capacity allows that the paper requirements of all facilities are satisfied from that plant. In most of the cases the needs of converting machines are much lower than the total installed capacity. Therefore the remaining paper production capacity is used for paper exports.

3.2.3 Product Families

Papers and some finished products are grouped in families for several reasons. The concerns in family compositions are different for papers and finished products.

Paper Families: As stated in Section 3.2.1, paper production contains chemical processes and production changes require costly setups, where chemicals of the last production should be removed from the mixing container. To eliminate those costly setups, paper production is designed as a continuous process, where the chemicals of next paper is directly fed into container without removing the remaining chemicals of last production. The consequence is that the chemicals of two papers produced in succession are obliged to be mixed in some quantities. There exists an exception for production with recycled papers, where the mixing container must be cleaned up after a paper production with recycled papers.

Papers differ in their purpose of use and quality level. Quality indicators depend on the type of the paper. For instance, softness and durability are two quality indicators for toilet papers, that is the quality of toilet paper increases with the increase in the level of softness and durability. Characteristics such as softness and durability are determined by the chemical ingredients of the paper. Since the quality of paper depends on the chemical ingredients, successive paper productions on the same resource should have similar ingredients to prevent loss in quality. For this reason, papers are divided into families with respect to the similarity of their chemical compounds. 60 different papers are grouped into approximately 15 paper families.

Since there exists 15 different types of paper families and only 3 paper machines, it is not always possible to produce papers belonging to the same family only on the same machine. Consequently, planners define some production change rules among paper families, so that the quality of papers is not harmed.

Finished Product Families: For the converting phase, product families are composed in such a way that the products having similar setup requirements belong to the same family. The major setup causing factor in converting phase is the change of paper bobbin. Hence, families are mainly defined by the paper types of products.

Planners define some production rules on product families so that setup requirements during converting phase are decreased. Some product families are produced only once in a month. That is, all monthly production requirements of products in that family are satisfied during a single production period. For some product families, planners want to force the production to continue at least for a minimum amount of time, which helps to limit the frequency of setups. Planners determine a fixed production sequence for some families on some resources during a month. Here again, the aim is to ensure minimum setup time spent on those resources.

4 Problem Definition

4.1 Basic Definitions

Every tangible item in the production system, such as raw materials, finished and semi-finished goods, is called a *part*. Every part $i \in I$ is either produced in one of the facilities or supplied from other companies. Some parts can be both purchased and produced. A *process* is an action which ensures the supply of a part. Set P_i contains all processes whereby part i can be provided, i.e. produced or purchased, where $|P_i| \geq 1$ for any $i \in I$. Let P'_i indicate all production processes and P''_i all procurement processes of part i, where $P'_i \cup P''_i = P_i$. Note that, $|P'_i| = 0$ for all parts $i \in M$. Production process p of a part $i \in F \cup S$ is defined by the resource where the production will take place and by the bill of materials which will be used during that process.

Each production process can be realized only on one resource. Let $r(p)$ define the resource of production process p, where $p \in P'_i$ for any $i \in F \cup S$. If part $i \in F$, then $r(p) \in R_f$ for every $p \in P'_i$. Similarly, if part $i \in S$, then $r(p) \in R_s$ for every $p \in P'_i$. Also let $P_i(r)$ be the set of processes of part i which are performed on resource r.

A part must be located in an inventory after realization of its procurement and/or production process. Let $k(p)$ indicate the inventory location where part i is placed after process p, where $p \in P_i$ and $k(p) \in K_i$. Also let $P_i(k)$ be the set of processes of part i after which part i is placed in inventory location k. For basic set definitions and parameters, reader is referred to Table 1.

Table 1 Basic definitions and parameters.

I	Set of *part*s, i.e. raw materials, finished and semi-finished goods, indexed by i.
F	Set of finished parts, i.e. output of converting phase.
S	Set of semi-finished parts, i.e. bulk papers.
M	Set of raw materials.
G	Set of all part families, indexed by g.
χ_{ig}	1 if part i is in family g; 0, otherwise.
P	Set of all *process*es, indexed by p.
P_i	Set of processes of part i.
R	Set of all resources, indexed by r.
R_s	Set of paper machines.
R_f	Set of converting lines.
K	Set of all inventory locations, indexed by k.
K_i	Set of inventory locations of part i.
Q	Set of all demand types, indexed by q, where every demand type is associated with a priority level.
R^q_{ij}	Quantity of jth demand for part i of type q, where $i \in F$.
d^q_{ij}	Due date of the jth requirement for part i.

4.2 Planning Problem and Problem Architecture

Planners are in charge of taking various planning decisions which can be grouped under long-term and short-term decisions.

Long-term decisions:

- Sales department generates forecasts for the sales of the next four months. Given those forecasts, capacity allocations among all production plants should be determined.
- Production requirements should be determined for each plant. Those requirements have to be determined at process level to clarify loads on machines and raw material requirements.

- Monthly material acquisition requirements should be provided for each plant.
- Monthly capacity availability for paper exports should be determined and sales department should be informed about the possible capacity allocation to be able to manage paper sales.
- Due to capacity allocations, labor force requirements for each plant and also for each resource should be determined, whereas the rules and regulations negotiated with the labor union should be obeyed.

Short-term decisions:

- The detailed production plan, i.e. quantities of every production batches, their start and completion times, should be provided for a short term (typically for two weeks).
- Quantity and dates of paper transshipments to other plants should be determined.
- Satisfaction of demands from various production batches should be determined.

Since there are different types and levels of decisions, we decomposed the problem into three separate problems: capacity planning, shift planning and scheduling. The problems are designed to be solved in a hierarchical manner, where they are connected by input-output relations (see Figure 3).

Monthly forecasts of sales department, capacity allocation agreements of contractors, acquisition plans of raw materials and minimum stock levels determined by planners are the main inputs of the capacity planning problem. In this problem monthly production requirements for each product and resource capacity requirements for these productions are determined. Based on those requirements, weekly shift plan of each resource are provided as a result of shift planning problem. Maintenance schedule and restrictions by labor law are further inputs of this problem.

Inputs of the scheduling problem mainly consist of the outputs of the capacity planning and the shift planning problem. The output of this problem is the production schedule for the next two weeks. Product family definitions, customer orders and sales channel priorities are other additional factors which are taken into consideration in the scheduling problem.

5 Solution Procedures

Considering the architecture in Figure 3 we constructed three models for three problems: capacity planning (Section 5.1), shift planning (Section 5.2) and scheduling (Section 5.3) models.

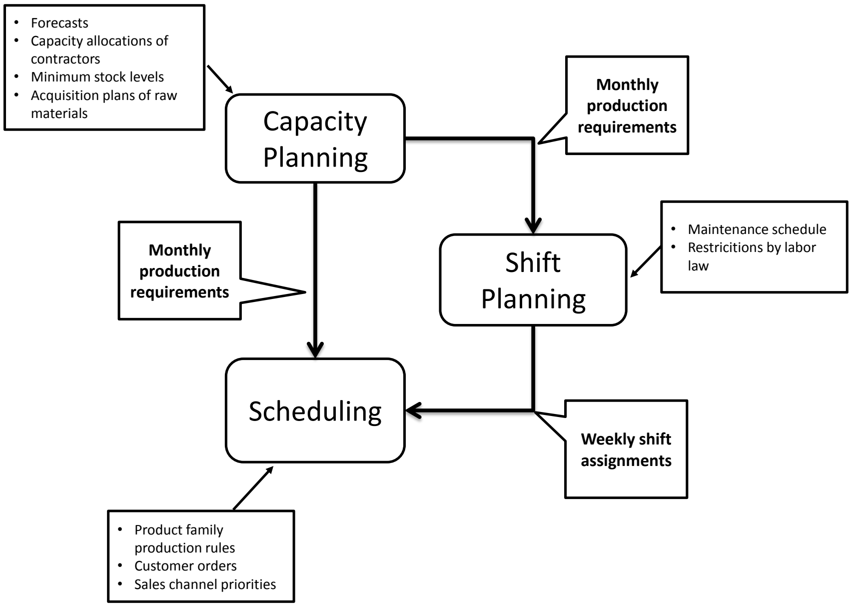

Fig. 3 Architecture of planning problem.

5.1 *Capacity Planning Model*

The capacity planning problem aims to determine production quantities based on the monthly forecasts. It is based on a linear programming (LP) model similar to a classical aggregate production planning model, where, in addition, a number of planning issues specific to company's needs are also considered.

Issue 1 *Some finished and semi-finished parts are forced to have a certain level of inventory at the end of a given period.*

In aggregate capacity planning, the assumption is that parts are produced during the period and demand for parts are satisfied at the end of the period. However in real life, demand may occur at any time during the month. Consider a finished part *i*, which sees a demand at the beginning of the period. It may be the case that the production of this part can only be started towards the end of the period. To be able to satisfy those early demands, the part should have some inventory at the beginning of that period. To ensure that, planners define minimum inventory levels for the parts which may require some stock at the beginning of a period.

Issue 2 *There are agreements on capacity allocation of contractors.*

Contractors' production activities mainly depend on the company's demand, since contractors do not have any other partners in their businesses. The capacity allocation agreements ensure for contractors the realization of a certain production level in every month. This is necessary for contractors to ensure the sustainability of their operations.

Issue 3 *There are fixed production orders which are released to shop floor.*

Planners control the production on the shop floor by releasing production orders for a time interval, which usually varies between two to four days.

Issue 4 *There exists a production sequence of part families that are produced on same resource within a period.*

In Section 3.2.3, we explained that there are product families in converting phase which require major setups during production change from one family to another. To prevent frequent setups, planners decide on a sequence for some part families on some resources. Hence, parts belonging to those families are produced in a sequence determined by the planner, where each part family is typically produced at most once in a period.

Figure 4 shows an example for this case. Here, A, B, C and D are part families, which are to be produced in the given sequence in periods t and $t+1$.

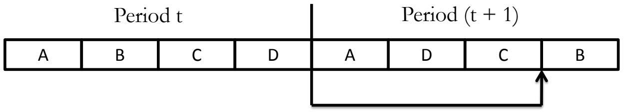

Fig. 4 An example for the production sequence of product families.

Consider product family B, which is to be produced as the second batch in period t and as the last batch in period $t+1$. The issue regarding the planning goals is that inventory levels of the parts 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 part family B starts in period $t+1$.

Issue 5 *Parts can be produced via different processes which have different priorities.*

A finished or semi-finished part can be produced through different processes. Processes differ in resource and materials used during the production. That is, the cost of production may differ for different processes. Therefore, planners define priorities among production processes of parts.

Since the production decisions are to be made based on monthly forecasts, we use monthly periods in capacity planning model. Let T define the planning horizon such that $t = 1, 2, \ldots, |T|$. Each $t \in T$ represents a calendar month. Sales department is usually able to forecast the demand of the next four months in advance.

Monthly production and procurement requirements are the main decision variables of CP model: x_{ipt} is the quantity of part i produced and/or procured in period t using the process p, where $i \in I$, $p \in P_i$ and $t \in T$.

Decision variables regarding ending inventory levels are used to manage production distribution among months. Variable I_{ikt} defines the inventory level of part i in inventory location k at the end of period t, where $i \in I$, $k \in K_i$ and $t \in T$. Let I_{ik0} be the parameter indicating the initial inventory level of part i in inventory location k, where $i \in I$, $k \in K_i$.

The company has a multi-facility production system as indicated in Section 3.2.2. Since paper production is executed only in one plant, the transshipment amounts of papers from one plant to the others have to be determined. y_{iklt} is the amount of part i transshipped from inventory location k to inventory location l in period t, where $i \in I$, $k, l \in K_i$ and $t \in T$.

Parameter ID_{it} represents the independent demand for part i for period t, where $i \in F$ and $t \in T$. Independent demands correspond to monthly forecasts on finished goods given by the sales department. Realized customer orders, i.e. orders which are already delivered to the customer, are excluded from the forecasts for the first month. DD_{it} is the variable indicating the dependent demand for part i in period t, where $i \in S \cup M$ and $t \in T$.

At any time there exists a shift plan for each resource which indicates the installed capacity, i.e. *regular* capacity, RC_{rt}, on that resource. Due to increase in production requirements, planners may decide to assign additional shifts for the required resources. We denote this available flexibility in capacity expansion by the parameter OC_{rt}. It indicates the additional capacity which can be added to resource r in period t. Note that, using additional capacity is more costly than using regular capacity.

CP Model:

$$\begin{aligned} \textbf{CP}\text{: } \min \; & \sum_{i \in I} \sum_{p \in P_i} \sum_{t \in T} c_{ip}\, x_{ipt} + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} h_{ik}\, I_{ikt} + \sum_{i \in I} \sum_{k \in K} \sum_{l \in K \setminus \{k\}} \sum_{t \in T} f_{ikl}\, y_{iklt} \\ & + \sum_{r \in R} \sum_{t \in T} rc_r\, rcu_{rt} + \sum_{r \in R} \sum_{t \in T} oc_r\, ocu_{rt} + \sum_{r \in R} \sum_{t \in T} ofc_r\, ofcu_{rt} \qquad (1) \end{aligned}$$

subject to

$$I_{ik,t-1} + \sum_{p \in P_i(k)} x_{ipt} + \sum_{l \in K_i \setminus \{k\}} y_{ilkt} - \sum_{l \in K_i \setminus \{k\}} y_{iklt} - ID_{it} = I_{ikt}$$
$$\forall i \in F,\ \forall k \in K_i \text{ and } \forall t \in T \qquad (2)$$

$$I_{ik,t-1} + \sum_{p \in P_i(k)} x_{ipt} + \sum_{l \in K \setminus \{k\}} y_{ilkt} - \sum_{l \in K \setminus \{k\}} y_{iklt} - DD_{it} = I_{ikt}$$
$$\forall i \in S \cup M,\ \forall k \in K_i \text{ and } \forall t \in T \qquad (3)$$

$$\sum_{i \in F \cup S} \sum_{p \in P_i} u_{ipj}\, x_{ipt} = DD_{jt} \quad \forall j \in S \cup M \text{ and } \forall t \in T \qquad (4)$$

$$\sum_{i \in F \cup S} \sum_{p \in P_i(r)} w_{ipr} x_{ipt} = rcu_{rt} + ocu_{rt} + ofcu_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{5}$$

$$rcu_{rt} \leq RC_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{6}$$

$$ocu_{rt} \leq OC_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{7}$$

$$I_{ikt} \geq s_{ikt} \quad \forall i \in F \cup S, k \in K_i \text{ and } \forall t \in T \tag{8}$$

$$x_{ipt} \geq z_{ipt} \quad \forall i \in F, \forall p \in P_i \text{ and } \forall t \in T \tag{9}$$

$$x_{ip,1} \geq o_{ip} \quad \forall i \in S \cup F \text{ and } \forall p \in P_i \tag{10}$$

$$I_{ikt} \geq \alpha_{ikt} \quad \forall i \text{ such that } \chi_{ig} = 1, \gamma(g,r,t) \text{ exists}, \forall r \in R^*, \forall t \in T \tag{11}$$

$$x_{ipt} \geq 0 \quad \forall i \in I, \forall p \in P_i \text{ and } \forall t \in T \tag{12}$$

$$I_{ikt} \geq 0 \quad \forall i \in I, \forall k \in K \text{ and } \forall t \in T \tag{13}$$

$$y_{iklt} \geq 0 \quad \forall i \in I, \forall k, l \in K \text{ and } \forall t \in T \tag{14}$$

$$DD_{it} \geq 0 \quad \forall i \in S \cup M \text{ and } \forall t \in T \tag{15}$$

$$rcu_{rt}, ocu_{rt}, ofcu_{rt} \geq 0 \quad \forall r \in R \text{ and } \forall t \in T \tag{16}$$

Objective of CP model is to minimize costs consisting of production, purchasing, resource usage, and inventory holding costs, where c_{ip}, h_{ik}, f_{ikl}, rc_r and oc_r are unit process, inventory holding, freight, regular capacity and additional capacity usage costs, respectively.

Constraints (2) and (3) are the inventory balance equations. Constraints (4) basically determine raw material requirements of finished and semi-finished parts and semi-finished part, i.e. paper, requirements of finished parts. The parameter u_{ipj} indicates the required quantity of part j for one unit of part i in process p. Constraints (5) formulate the resource usages of finished and semi-finished parts. The parameter w_{ipr} indicates the unit processing time of part i in process p on resource r. The variables $ofcu_{rt}$ in Constraints (5) indicate the $overflow$ capacity usage of resource r in period t. Those variables are used to capture infeasibilities of the model, if there exist more production requirements than a resource can produce. That is, variables $ofcu_{rt}$ have positive values if and only if a resource cannot satisfy production requirements by operating 7x24. Constraints (6) and (7) set upper bounds to resource usages.

Constraints (8) handle Issue 1, where s_{ikt} is the desired minimum ending inventory level for part i in inventory location k at the end of period t. Constraints (9) handle Issue 2, where z_{ipt} is the minimum production quantity determined by the planners for part i through process p in period t. Issue 3 is handled by Constraints (10), where o_{ip} is the production order quantity of part i through process p. Issue 4 is handled by Constraints (11), where α_{ikt} is the minimum ending inventory level of part i in inventory location k for period t such that it can cover the demand until production of the family of part i starts in period $t+1$ and $\gamma(g,r,t)$ indicates the sequence of part family g on resource r in period t. R^* is the set of resources for which a family sequence is given.

In implementation of CP model in real life, the number of decision variables and constraints are approximately 72000 and 32000, respectively. The construction of the optimization model and its solution process take less than two minutes.

5.2 Shift Planning Model

The company can operate on various shift plans in accordance with its agreements with the labor union such as 8:00–16:00, 8:00–00:00, 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. Table 2 shows the working hours and days of all shift types.

Table 2 Shift definitions.

Shift Type	Working Hours	Working Days
0	N/A	N/A
1	8:00–16:00	Monday–Saturday
2	8:00–00:00	Monday–Saturday
3	All day	Monday–Saturday
4	All day	Monday–Sunday

Let S define the set of shift types, where $s \in S$ and $S = \{0,1,2,3,4\}$. The working days and working hours in a day change due to shift type. Let d_s be the number of working days in a week and let h_s be the number of working hours in a day due to shift type s (see Table 3).

Table 3 Number of working hours and working days of each shift type.

s	h_s	d_s
0	0	0
1	8	6
2	16	6
3	24	6
4	24	7

The planning horizon of shift planning problem covers the planning horizon of capacity planning problem, which is T and for every period t is defined as $t = 1,2,\ldots,|T|$. Let W be the set of weeks in planning horizon T, where $w = 1,2,\ldots,|W|$. Some $w \in W$ are fully contained by a period t and some $w \in W$ are contained by two periods. Let W_t be the set of weeks which coincide with period t and let D_{wt} be the set of days in week w and in period t.

The aim of shift planning model (SPM) is to generate weekly shift assignments for all resources in accordance with the following planning issues.

Issue 6 *Installed capacity generated by the shift plan should meet the requirements due to results of capacity planning model.*

Due to capacity allocations given by the capacity planning problem weekly shift assignments on resources have to be determined. Since installed capacity by shift plan should cover monthly capacity requirements, i.e. rcu_{rt} and ocu_{rt}, are taken as inputs from capacity planning problem.

Issue 7 *If shift type 4 is assigned to a week and the successive week has another shift assignment, the operators do not work on Sunday in the week with shift type 4.*

Issue 7 is related with shop floor practice. If shift type 4 is assigned for a series of weeks, on Sunday of the last week with shift type 4, the resource is not operated.

Issue 8 *Frequent shift type changes on a resource should be prevented.*

There may be alternative shift assignments which provide same capacity installation so that generated shift plan does not contradict with Issue 6. From those alternatives, the one with the least shift type change should be selected.

Issue 9 *Shift change between successive weeks may not be greater than one.*

This issue states that there should not be drastic shift changes between the weeks.

Issue 10 *The shift plan of the first week cannot be changed.*

Due to limitations in labor arrangements, the shift assignments of the first week cannot be changed.

Issue 11 *Planners may decide to fix some shift assignments of some weeks.*

Some shift assignments may be predetermined by the planners such that they cannot be changed by the model.

The shift planning problem can be solved independently for each resource, since there does not exist any constraint which relates shift assignments of different resources (each machine has its own dedicated employees). Thus, we construct a mixed-integer programming (MIP) model for each resource separately. Main decision variables of our model represent the shift plan assigned to the resource for each week.

$$y_{sw} = \begin{cases} 1 \text{ if shift } s \text{ is assigned for week } w \\ 0 \text{ otherwise} \end{cases}$$

where $s \in S$ and $w \in W$.

SP model for all $r \in R$:

$$\mathbf{SP}(r)\text{:}\ \min \sum_{t\in T}\sum_{w\in W_t}\sum_{s\in S} h_s\, d_{swt}\, y_{sw} + \sum_{w\in W} \beta_w \tag{17}$$

subject to

$$\sum_{s\in S} y_{sw} = 1, \quad \forall w \in W \tag{18}$$

$$\sum_{w\in W_t}\sum_{s\in S} h_s\, d_{swt}\, y_{sw} - (24)\omega_w \geq (rcu_{rt} + ocu_{rt})\,\frac{1}{3600}, \quad \forall t \in T \tag{19}$$

$$y_{4w} + y_{s,w+1} \leq \omega_w + 1, \quad \forall w \in W\backslash\{|W|\} \text{ and } \forall s \in S\backslash\{4\} \tag{20}$$

$$\sum_{s\in S} g_s\, y_{sw} - \sum_{s'\in S} g_{s'}\, y_{s',w-1} \leq \beta_w, \quad \forall w \in W\backslash\{1\} \tag{21}$$

$$\sum_{s'\in S} g_{s'}\, y_{s',w-1} - \sum_{s\in S} g_s\, y_{sw} \leq \beta_w, \quad \forall w \in W\backslash\{1\} \tag{22}$$

$$\sum_{s\in S} g_s\, y_{sw} - \sum_{s'\in S} g_{s'}\, y_{s',w-1} \leq 1, \quad \forall w \in W\backslash\{1\} \tag{23}$$

$$\sum_{s\in S} g_s\, y_{sw} - \sum_{s'\in S} g_{s'}\, y_{s',w-1} \leq 1, \quad \forall w \in W\backslash\{1\} \tag{24}$$

$$y_{\psi 1} = 1 \tag{25}$$

$$y_{\gamma_w w} = 1, \quad \forall w \in W' \tag{26}$$

$$y_{sw} \in \{0,1\} \quad \forall s \in S \text{ and } \forall w \in W \tag{27}$$

$$\omega_w \in \{0,1\} \quad w = 1,2,\ldots,|W|-1 \tag{28}$$

$$\beta_w\ \geq 0 \quad \forall w \in W \tag{29}$$

Objective of SP model is to minimize total working hours and total number of shift changes.

Constraints (18) ensure that there is only one shift assignment for each week. Constraints (19) handle Issue 6, where the resource usages are given in seconds. The term $h_s\, d_{swt}$ indicates the working hours of week w for shift type s which will be available in period t. The term $\omega_w * 24$ stands for a possible 24 hour capacity loss due to Issue 7.

Constraints (20) calculate the capacity loss due to Issue 7, i.e. ω_w, which is 1 if shift type 4 is assigned to week w and another shift type is assigned to week $w+1$, and 0 otherwise.

Constraints (21) and (22) handle Issue 8, where variable β_w controls the change in shift assignments between consecutive weeks. Here, $g_s = |s|$ for all $s \in S$. Issue 9 is handled by Constraints (23) and (24). Here, it is ensured that the shift type changes between successive weeks do not exceed 1.

Constraint (25) handles Issue 10, where ψ is the shift assigned to resource r. Issue 11 is handled by Constraints (26), where γ_w is the assigned shift for week w, $\gamma_w \in S$ and W' indicates set of weeks whose shift assignment is fixed.

In real life application, the MIP model for a single resource consists of around 120 decision variables and 150 constraints. Around 100 decision variables of the model are binary variables. Construction and solution of the model to optimality typically takes less than twenty seconds.

5.3 Scheduling Model

The scheduling problem deals with determination of production batches for finished and semi-finished parts. Main inputs are received from capacity planning and shift planning problems:

- Monthly production requirements for finished and semi-finished parts, i.e. x_{ipt}, where $i \in F \cup S$, $p \in P_i^{'}$ and $t \in T$. Here, $P_i^{'}$ only includes the production processes of part i.

- Weekly shift assignments, which determine the installed capacities on resources and the times when each resource starts and ends operating during the day.

Given the total production requirements, we want to determine a series of production batches for finished and semi-finished parts, where we also consider the following planning issues:

Issue 12 *There exist minimum production lot constraints for finished and semi-finished parts.*

Planners define minimum production lot quantities for finished and semi-finished parts to increase production efficiency and to avoid frequent setups.

Issue 13 *Output of scheduling model should match with monthly production quantities generated by CP model.*

Scheduling problem takes process based production requirements from CP model. Since the capacity allocation decisions are taken in CPM level, scheduling results should comply with the production decisions of CP model.

Issue 14 *Some families are produced once in a month.*

To be able to minimize setup requirements, some part families are produced only once in a month. That is, all production requirements of part in those families have to be satisfied within the time interval where the family is being produced.

Issue 15 *Some part families have restrictions on their minimum production duration.*

The planners decide on a minimum production duration for some part families to avoid frequent setup requirements.

Issue 16 *Schedule of part families with given sequence must comply with that sequence.*

In Issue 4 of CP model, we consider the monthly part family sequence determined by planners. Same input is also considered in scheduling problem.

Issue 17 *There are production change rules between paper families.*

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 different papers contain different and sometimes incompatible chemical compounds, transition between some paper types have to be prohibited. For this reason, planners group products having similar properties into families and define a set of transition rules.

Scheduling model (SM) generates a detailed schedule for a short-term planning horizon, which is typically the next two weeks, by using a two-phase scheduling algorithm. The output of scheduling model is the size, start and completion times of those production batches. Let $B_{ip}^{[j]}$ be the jth production batch for part i produced by process p and let $|B_{ip}^{[j]}|$ indicate the size of the batch $B_{ip}^{[j]}$. We define $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$ as the start and completion times of batch $B_{ip}^{[j]}$, respectively.

In the first phase of the scheduling algorithm, we solve an optimization model (batch sizing model) to determine the optimum production batch sizes. The second phase generates a feasible sequence of the resulting batches on the selected machine using a heuristic procedure. That is, first phase determines size of production batches, $|B_{ip}^{[j]}|$'s, and second phase sets $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$'s.

5.3.1 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 shift 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 planning horizon and time periods are shortened. Let B be the planning horizon for the batch sizing model where $b = 1, 2, \ldots, |B|$. The planning horizon B covers next two months and each period $b \in B$ has a length of 3 days. Let $s(b)$ and $e(b)$ indicate start and end times of a period b.

Let x_{ipb} be the production quantity of part i through process p in period b, where $i \in F \cup S$, $p \in P_i$ and $b \in B$. And let y_{ipb} be the binary variable such that

$$y_{ipb} = \begin{cases} 1 & \text{if part } i \text{ will be produced via process } p \text{ in period } b \\ 0 & \text{otherwise} \end{cases}$$

where $i \in F \cup S$, $p \in P_i$ and $b \in B$.

There are different types of requirements which should be satisfied by the production batches. For this MIP model, requirements are grouped for each period and each requirement type and the sum of requirements is defined as the demand for the related period. Those requirements include customer orders of different sales channels in addition to the forecasts given by the sales department. For this model, monthly forecasts are evenly distributed among periods in B. We define ID_{ib}^{q} as the demand for part i in period t of type q. Following calculation is done for all requirement types other than forecasts:

$$ID^q_{ib} = \sum_{s(b) \le d^q_{iu} < e(b)} R^q_{iu}$$

where $i \in F$ and $b \in B$. For forecasts we have the following calculations. Here, q' stands for requirement type for forecasts.

$$ID^{q'}_{ib} = \frac{ID_{it}}{|B(t)|}$$

where $i \in F$ and $b \in B$. ID_{it} is the monthly forecast of part i for monthly period t. $B(t)$ indicates the set of periods of length three days which are in the monthly period t. Different types of requirements mean different priorities, that is the late satisfaction of high priority requirements are penalized more than others. Here, forecasts have the lowest priority among all requirements.

Let x^q_{ib} be the production quantity of part i in period b to satisfy the requirement type q, where $i \in F$ and $b \in B$. Also let I^q_{ib} be inventory level of type q for part i at the end of period b, where $i \in F$ and $b \in B$. It is possible that some requirements cannot be satisfied on time for some technical issues. To manage this, we define a variable U^q_{ib} for unsatisfied requirement quantity of part i for requirement type q in period b.

In the MIP model, there exist part family related constraints. To be able to keep track of whether a part family g is produced in a period b, we define another binary variable v_{grb}:

$$v_{grb} = \begin{cases} 1 \text{ if part family } g \text{ will be produced on resource } r \text{ in period } b \\ 0 \text{ otherwise} \end{cases}$$

where $g \in G$, $r \in R$ and $b \in B$.

Resource capacities for each period is calculated given the shift plan generated by the shift planning model. Let C_{rb} be the capacity (in seconds) of resource r in period b, where $r \in R$ and $b \in B$. C_{rb}'s are calculated using the output of SPM as follows:

$$C_{rb} = \sum_{w \in W(b)} \sum_{s \in S} h_s \, d_{swb} \, y_{rsw}$$

Here, S is the set of all shift types, h_s is the working hours in a day for shift type s. Period b may coincide with more than one week. $W(b)$ defines the set of weeks, which contain some portion of period b. d_{swb} defines the number of working days in period b due to shift type s assigned to week w. y_{rsw} is the output of SPM, which has value 1 if shift s is assigned to resource r for week w, and 0, otherwise. For capacity usages we define variable u_{rb}, where $r \in R$ and $b \in B$.

Batch sizing model is an MIP model, which can be formulated as follows:

$$\begin{aligned}\textbf{BSM}\text{: } \min &\sum_{i\in I}\sum_{p\in P_i}\sum_{b\in B} c_{ip}\, x_{ipb} + \sum_{i\in F}\sum_{q\in Q}\sum_{b\in B} h_i^q\, I_{ib}^q + \sum_{i\in S}\sum_{k\in K_i}\sum_{b\in B} h_{ik}\, I_{ikb} \\ &+ \sum_{i\in I}\sum_{q\in Q}\sum_{b\in B} u_i^q\, U_{ib}^q + \sum_{i\in S}\sum_{k\in K_i}\sum_{l\in K_i\setminus\{k\}}\sum_{b\in B} f_{ikl}\, z_{iklb} + \sum_{r\in R}\sum_{b\in B} ru_r\, u_{rb}\end{aligned} \tag{30}$$

subject to

$$I_{i,b-1}^q + x_{ib}^q - ID_{ib}^q + U_{ib}^q - U_{i,b-1}^q = I_{ib}^q, \quad \forall q\in Q, \forall i\in F, \forall b\in B \tag{31}$$

$$I_{i,0} = \sum_q I_{i,0}^q \quad \forall i\in F \tag{32}$$

$$\sum_{p\in P_i} x_{ipb} = \sum_{q\in Q} x_{ib}^q \quad \forall i\in F, \forall b\in B \tag{33}$$

$$\sum_{i\in F}\sum_{p\in P_i} b_{ipj}\, x_{ipb} = DD_{jb} \quad \forall j\in S, b\in B \tag{34}$$

$$\begin{aligned} I_{ik,b-1} + \sum_{p\in P_i(k)} x_{ipb} + \sum_{l\in K\setminus\{k\}} z_{ilkb} - \sum_{l\in K\setminus\{k\}} z_{iklb} - DD_{ib} = I_{ikb} \\ \forall j\in S, k\in K_i, b\in B\end{aligned} \tag{35}$$

$$x_{ipb} \le M\, y_{ipb} \quad \forall i\in F\cup S, p\in P_i, b\in B \tag{36}$$

$$\sum_{i\in I}\sum_{p\in P_i} a_{ipr}\, x_{ipb} \le C_{rb} \quad \forall r\in R, b\in B \tag{37}$$

$$x_{ipb} \ge \mu_i\, y_{ipb} \quad \forall i\in F\cup S, p\in P_i \text{ and } b\in B \tag{38}$$

$$\sum_{b\in B(t)} x_{ipb} = X_{ipt} \quad \forall i\in F\cup S, \forall p\in P_i \text{ and } \forall t\in T \tag{39}$$

$$v_{grb} \ge \chi_{ig}\, y_{ipb} \quad \forall i\in F\cup S, \forall p\in P_i(r), \forall g\in G, \forall b\in B \tag{40}$$

$$v_{grb}^s + v_{grb}^e + v_{grb}^c = v_{grb} \quad \forall g\in G', r\in R, b\in B \tag{41}$$

$$\sum_{b\in B(t)} v_{grb}^s \le 1 \quad \forall g\in G', r\in R, t\in T \tag{42}$$

$$\sum_{b\in B(t)} v_{grt}^e \le 1 \quad \forall g\in G', r\in R, t\in T \tag{43}$$

$$\sum_{b\le b^*} v_{grb}^s \ge v_{grb^*}^e \quad \forall g\in G', r\in R, \forall b^*\in B \tag{44}$$

$$\begin{aligned} v_{grb^-} + v_{grb^+} = v_{grb} + 1 \quad \forall g\in G', r\in R, \forall b, b^+, b^-\in B \\ \text{such that } b^- < b < b^+\end{aligned} \tag{45}$$

$$\sum_{i\in F}\sum_{p\in P_i(r)} \chi_{ig}\, a_{ipr}\, x_{ipb} \ge v_{grb}\, \tau_g \quad \forall g\in G'', r\in R, \forall b\in B \tag{46}$$

$$\begin{aligned} x_{ipb^*} = 0 \quad \forall i \text{ such that } \chi_{i,g_j} = 1, p\in P_i(r), \forall g\in G''', \forall b^* \\ \text{such that } b'_{g_j,t} > b^* \text{ or } b''_{g_j,t} < b^* \text{ and } \forall t\in T\end{aligned} \tag{47}$$

$$v_{g_j rb} + v_{g_l rb} = v_{g_k rb} + 1 \quad \forall g_j, g_k, g_l \in G^s \text{ such that } g_j \prec g_k \prec g_l, \forall b\in B \tag{48}$$

$$x_{ipb} \ge 0 \quad \forall i\in F\cup S, \forall p\in P_i, \forall b\in B \tag{49}$$

$$I_{ib}^q, U_{ib}^q, x_{ib}^q \ge 0 \quad \forall i\in F, \forall q\in Q, \forall b\in B \tag{50}$$

$$I_{i0}^q \ge 0 \quad \forall i\in F, \forall q\in Q \tag{51}$$

$$I_{ikb} \ge 0 \quad \forall i\in S, \forall k\in K_i, \forall b\in B \tag{52}$$

$$z_{iklb} \ge 0 \quad \forall i\in S, \forall k, l\in K_i, \forall b\in B \tag{53}$$

$$DD_{ib} \ge 0 \quad \forall i\in S, \forall b\in B \tag{54}$$

$$u_{rb} \ge 0 \quad \forall r\in R, \forall b\in B \tag{55}$$

$$y_{ipb} \in \{0,1\} \quad \forall i\in F\cup S, \forall p\in P_i, \forall b\in B \tag{56}$$

$$v_{grb} \in \{0,1\} \quad \forall g\in G, \forall r\in R, \forall b\in B \tag{57}$$

$$v_{grb}^s, v_{grb}^c, v_{grb}^e \in \{0,1\} \quad \forall g\in G', \forall r\in R, \forall b\in B \tag{58}$$

The objective of batch sizing model is to minimize the total cost of production, resource usage, inventory holding, transportation and unsatisfied demand costs. Here, c_{ip}, h_i^q, h_{ik} u_i^q, f_{ikl} and ru_r are the unit production, inventory holding for finished and semi-finished parts, unsatisfied demand associated with demand type q, transportation and resource usage costs, respectively.

Constraints (31) and (35) are inventory balance equations for finished and semi-finished parts, respectively. Constraints (32) and (33) handle the distribution of initial inventory and production requirements of finished parts among inventories and production with different (demand) types. Constraints (34) determine dependent demand for semi-finished parts, where, b_{ipj} indicates the quantity of part j used by part i in process p. Constraints (36) determine the value of the binary variable indicating the existence of a production in a period. Constraints (37) are resource capacity constraints, where a_{ipr} is the unit processing time of part i on resource r in process p.

Constraints (38) handle Issue 12, where μ_i is this minimum lot quantity. Issue 13 is handled by the set of periods which are in month t. Constraints (39), where X_{ipt} indicates the production requirement for part i via process p in month t.

Constraints (40) ensure that v_{grb} is assigned to 1, if at least one of the parts in that family has a production in period b on resource r.

Issue 14 is handled by Constraints (41), (42), (43), (44) and (45), where G' be the set of families which have to be handled by Issue 14. Since production of families usually take longer than one period, the production of a family in successive periods should be controlled. Variables v^s_{grb}, v^e_{grb} and v^c_{grb} are equal to 1 if part family g starts, ends or continues production, respectively, on resource r in period b, or 0 otherwise.

Constraints (46) handle Issue 15, where G'' is the set of families which have a minimum production duration, τ_g, defined for part family g.

Constraints (47) handle Issue 16, where G''' is the part families for which a production sequence is given on a resource r. Given the sequence and monthly production requirements, we can determine the periods in which a part family is going to be produced. We call $b'_{g_j,t}$ and $b''_{g_j,t}$ be start and end periods for production of family g_j in month t, respectively.

Issue 17 is handled by Constraints (48), where $g_j \prec g_k \prec g_l$ indicates production transition rule between semi-finished part families g_i, g_j and g_k, that is family k has to be produced between families j and i. Here G^s is the set of semi-finished part families and g_i, g_j and $g_k \in G_s$.

The number of decision variables and constraints in batch sizing model are approximately 43000 and 23000, respectively. It is complicated to generate an optimal solution in reasonable amount of time for a MIP model in that size. For this reason, we ask planners to determine the number of periods where they want to see detailed schedule and we relax all remaining binary variables. This time period usually has a length of two weeks. Nevertheless, approximately 30% of all decision variables are binary variables and hence it is still complicated to solve the resulting MIP 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.

5.3.2 Sequencing of Production Batches

The BSM assigns production batches to resources for every time period, that is it determines $|B_{ip}^{[j]}|$'s for every part $i \in F \cup S$. However, BSM does not sequence the batches, which means that $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$'s are not determined.

After BSM, 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, which has an execution time not greater than twenty seconds. 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, i.e. the time when the projected inventory of a semi-finished good reaches zero due to finished part schedule
4. For finished goods, the total forecast 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. The scheduling algorithm is shown in Algorithm 1.

Algorithm 1 Scheduling Algorithm.

```
Create production batches: $B_{ip}^{[j]}$ $\forall i \in F \cup S$, $\forall p \in P_i$ and $\forall b \in B$.
$|B_{ip}^{[j]}| \leftarrow x_{ipb}$.
Schedule converting batches. (Algorithm 2)
Schedule paper production batches. (Algorithm 3)
Reschedule converting production batches given paper availabilities. (Algorithm 4)
```

In the first step of Scheduling Algorithm, for every positive x_{ipb} a production batch $B_{ip}^{[j]}$ is created, where $[j] = b$ and

$$|B_{ip}^{[j]}| = x_{ipb}.$$

In the algorithm shown in Algorithm 2, start and completion times for production batches of finished parts, i.e. $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$ where $i \in F$, are determined due to a number of sorting criteria. Let $\pi(B_{ip}^{[j]})$ indicate the priority index of batch $B_{ip}^{[j]}$.

Algorithm 2 Schedule converting batches.

```
Calculate $\pi(B_{ip}^{[j]}) \; \forall i \in F$.
Determine set of requirements, i.e. $R_i^{[j]}$, which will be satisfied from batch $B_{ip}^{[j]}$.
$\pi(B_{ip}^{[j]})$ is given by the maximum requirement priority among satisfied requirements in $R_i^{[j]}$.
Sort $B_{ip}^{[j]}$'s with respect to following criteria:
Assigned period of $B_{ip}^{[j]}$, i.e. $[j]$.
Part family rules if part $i$ is a member of any part family in $G$.
$\pi(B_{ip}^{[j]})$.
Set $ST(B_{ip}^{[j]}) = \max_{j' \leq j \text{ and } k \in F}\{CT(B_{kp}^{[j']})\} + s_{ik}$ where $s_{ik}$ stands for the setup required between parts $i$ and $k$.
Set $CT(B_{ip}^{[j]}) = ST(B_{ip}^{[j]}) + |B_{ip}^{[j]}| a_{ipr}$, where $a_{ipr}$ is unit production duration on resource $r$ through process $p$.
```

In the algorithm shown in Algorithm 3, start and completion times for production batches of semi-finished parts, i.e. $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$ where $i \in S$, are determined due to the requirements generated by the converting schedule and paper production change rules. Here again, let $\pi(B_{ip}^{[j]})$ indicate the priority index of batch $B_{ip}^{[j]}$.

Algorithm 3 Schedule paper batches.

```
Calculate $\pi(B_{ip}^{[j]}) \; \forall i \in S$.
Calculate projected inventory for all $i \in S$ due to paper usages of batches $B_{kp}^{[j]}$ for all $k \in F$.
$\pi(B_{ip}^{[j]})$ is determined by the time that the stock level of paper $i$ reaches to zero.
Sort $B_{ip}^{[j]}$'s with respect to following criteria:
Assigned period of $B_{ip}^{[j]}$, i.e. $[j]$.
Paper production change rules.
$\pi(B_{ip}^{[j]})$.
Set $ST(B_{ip}^{[j]}) = \max_{j' \leq j \text{ and } k \in S}\{CT(B_{kp}^{[j']})\} + s_{ik}$ where $s_{ik}$ stands for the setup required between parts $i$ and $k$.
Set $CT(B_{ip}^{[j]}) = ST(B_{ip}^{[j]}) + |B_{ip}^{[j]}| a_{ipr}$, where $a_{ipr}$ is unit production duration on resource $r$ through process $p$.
```

Due to paper schedule, the availabilities of papers can be calculated. In the algorithm shown in Algorithm 4, start and completion times for production batches of finished parts, i.e. $ST(B_{ip}^{[j]})$ and $CT(B_{ip}^{[j]})$ where $i \in F$, are recalculated given the paper availabilities and the same sorting criteria as in the algorithm shown in Algorithm 2.

Algorithm 4 Reschedule converting batches.

```
Sort $B_{ip}^{[j]}$'s with respect to following criteria:
Assigned period of $B_{ip}^{[j]}$, i.e. $[j]$.
Part family rules if part $i$ is a member of any part family in $G$.
$\pi(B_{ip}^{[j]})$.
for All batches in sequence do
    Pick the first batch in sequence.
    Determine the earliest time $ES_i$ that the paper which is used by batch $B_{ip}^{[j]}$ is ready to use.
    Set $ST(B_{ip}^{[j]}) = \max\{ES_i, \max_{j' \leq j \text{ and } k \in F}\{CT(B_{kp}^{[j']})\} + s_{ik}\}$ where $s_{ik}$ stands for the setup required between parts $i$ and $k$.
    Set $CT(B_{ip}^{[j]}) = ST(B_{ip}^{[j]}) + |B_{ip}^{[j]}|\, a_{ipr}$, where $a_{ipr}$ is unit production duration on resource $r$ through process $p$.
    Recalculate the availability of paper used by $B_{ip}^{[j]}$.
    Remove scheduled batch from sequence.
end for
```

6 Implementation

Mathematical models and sequencing algorithms are implemented on ICRON Supply Chain Optimization System [15]. ICRON is an object oriented modeling system and it provides a visual algorithm development environment. It is highly flexible for implementing optimization models, heuristic and exact solution algorithms. ICRON is also capable of communicating with other systems such as ERP or database management systems. [15]

6.1 Integration of Models

By the design of problem architecture (Figure 3), capacity planning, shift planning and scheduling models are integrated to each other and they run in hierarchical order. Figure 5 summarizes this sequence.

Capacity planning model (CPM) has two run modes: *monthly* and *daily* modes. At the beginning of each month, sales department generates new forecasts for the next four months. Based on those new forecasts, CPM runs to generate monthly production requirements where the resource capacities are assumed to be at their

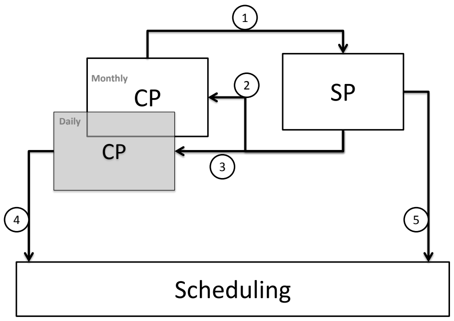

Fig. 5 Integration of three models.

maximum possible level. That is, resource capacities are calculated such that each of them is going to operate 7x24. Resulting production quantities are fed to shift planning model (SPM) to determine weekly shift plan for the next four months (see (1) in Figure 5). Planners may adjust the output of SPM due to some exceptional needs (see Section 6.2 for the possible manual overrides). After the adjustments, weekly shift plan is sent to CPM to adjust the production plan accordingly. In this second run of *monthly* CPM, resource capacities are calculated based on the weekly shift plan (see (2) in Figure 5).

It is highly possible that the monthly capacities generated by shift plan exceeds the required capacity with respect to the production requirements, since the shift assignments are discrete. For instance, if the required capacity for a resource during a month is 30 hours due to existing demand forecasts, the smallest shift assignment for that resource is obtained by assigning shift type 1 to one week and 0 to the remaining weeks. Total working hours in that month is going to be 48, since there is 6 working days for each week and 8 working hours for each day. It is not costwise reasonable to shut down the resource for the remaining 18 hours. For this reason, the shift plan generated by SPM is taken by the CPM to recalculate the production quantities. This step is an adjustment step where the monthly production and material requirements are recalculated.

The sales and production environment of the company is highly dynamic. It is quite common that Sales and Marketing Department adjusts the forecasts during the month due to changing customer orders and market conditions. To reflect those changes on the production plan, CPM runs in *daily* mode, where the installed capacities generated by SPM are considered as regular capacity for resources (see (3) in Figure 5). In this mode, the model allows deviations from installed capacities by SPM by additional capacities for additional costs which are higher than the cost of using regular capacity. If the model ends up with a solution where additional resource capacity is required, the planners are informed to run SPM to adjust the shift plan accordingly. Here, it is optional to run SPM for all resources or for a subset of them.

The monthly production plan generated by CPM and shift plan generated by SPM are provided as inputs for Scheduling Model (SM) to generate a detailed schedule for a short-term planning horizon, which is typically next two weeks (see (4) and (5) in Figure 5). The model runs usually following the run of *daily* CPM. The run of the model may also be triggered by changes occurred in master data or in shop floor. In Section 6.2, we provide information about further triggers initiated by planners to run SM.

6.2 Manual Overrides

The data for models are gathered from a number of sources such as ERP, shop floor, input data generated by planners etc. Besides those data sources, there are further occurrences in real life which have to be involved in planning process and which are difficult to transfer in written data. Following are some examples for such cases: phone calls from various departments, a sudden breakdown in shop floor or planners' own experiences about changing market conditions. We developed manual override mechanisms to help planners include this information in planning decisions.

6.2.1 Capacity Planning

- Towards the end of the first month, planners may decide to end the production of some parts, even if the minimum stock requirements defined earlier are not fully satisfied (Issues 1 and 4 in Section 5.1). In CPM, we create an additional constraint for every selected part to set the production quantities for first month to zero. To prevent infeasibility due to minimum inventory level constraints (constraints (8) and (11) in CPM), we remove those constraints related with the selected parts for the first period.
- To control resource allocations and raw material usages, planners may set a minimum production level to a production process which is usually a less preferred one according to original data. To handle this, we insert new constraints for each selected production process, where the minimum production quantities given by planners are set as lower bounds for corresponding decision variables.

6.2.2 Shift Planning

- As indicated in Section 5.2, Issue 11, planners may decide to fix shift plans for some weeks for various reasons. For the weeks which has a fixed shift assignment, we create constraints shown in 26. Planners may change their decisions and run SPM to adjust the shift plan.

- While explaining the details about integration of models in Section 6.1, we mentioned that the changes in monthly production plan may require changes in shift plan. If a change is required, planners are informed to make adjustments: they may re-run SPM or change the shift assignments manually by increasing or decreasing the assigned shift for every week whenever a change is needed.

6.2.3 Scheduling

The scheduling part of the system basically deals with the daily decisions in production management. The manual override mechanisms in this part helps planners to include sudden changes in the planning and production environment in the current plan immediately. These mechanisms work fast, hence they increase the responsiveness of the system. Furthermore the feasibility of the plan is maintained, so that planners do not have to worry about the implications of the changes they make.

Following manual override mechanisms are implemented. After every override action, batches are rescheduled. Rescheduling is needed due to possible changes of paper availability and changes in projected inventories of parts which may cause changes in requirement satisfaction assignments.

- Changing the order of production batches: Changes in customer orders, changes in acquisition plan or other reasons may effect the priorities of production batches. Planners may change the order of a converting or a paper production batch. If the new order violates some family setup rules, planners are warned about the implication of the last change. The order change in converting lines and paper machines are treated differently.
- Changing the size of a production batch: Planners may decide to change the amount of a production batch due to similar reasons as above. Violation of minimum production lot constraints or generation of additional paper requirement which is more than the maximum paper availability are possible causes of infeasibility. Planners have the option to leave the infeasibilities as they are, make the schedule feasible by themselves or withdraw the last change. The batch size change in converting lines and paper machines are treated differently.
- Changing the resource of a production batch: Some products can be obtained by several processes on different resources. It is possible that the planners have to change the assigned resource of a production batch. Breakdown of a machine, or late delivery of a material specific to the machine are potential causes for these changes. Those changes are also treated differently for converting and paper production phases.

7 Conclusion

In this study, we developed an integrated planning system at the largest tissue paper manufacturing company in Turkey. The company operates in a multi-facility production environment. As the nature of the sector, the environment is highly competitive and, hence, highly dynamic. The planning department is in the duty of generating the best production plan in long and short term to be able to compete in this dynamic environment.

The planning problem is decomposed into three subproblems, i.e. capacity planning, shift planning and scheduling, where the subproblems are solved in hierarchical manner. In capacity planning, the aim is to determine monthly production and capacity allocation requirements given the monthly forecasts generated by the sales department. Shift planning generates an appropriate shift plan, which consists of weekly shift assignments, given the production requirements and regulations of labor union. In scheduling phase, detailed production plan consisting of size, resource assignments, start and completion times of production batches is generated for the short term planning horizon.

Capacity planning problem is modeled as a linear programming (LP) model, which is very similar to classical aggregate production planning problem. Shift planning model is a mixed integer programming (MIP) model, which is constructed separately for each resource. Scheduling problem is solved by a two phase scheduling algorithm, where in first step, a mixed integer programming (MIP) model, i.e. batch sizing model, is solved. Model is very similar to capacity planning model, where it has smaller time buckets, shorter planning horizon and additional constraints which are not taken into account in higher level. After the model determines size and resource assignments of production batches, they are scheduled using a heuristic procedure.

All three modules are implemented using the development environment provided by ICRON Supply Chain Optimization System [15]. The developed planning system operates integrated with other systems of the company such as ERP, Production Management System (PMS) and other data sources. Data flows related with planning activities are maintained by ICRON. The planning system also supports interactions of planning department with other departments such as sales department and shop floor management.

The capacity planning and shift planning modules have been in use since January 2011, while the scheduling module became operational in March 2011. The company observed a number of benefits of using the planning system such as improved customer service level, improved responsiveness, and improved inventory mix.

Optimization of inventory flow resulted in an improved inventory mix, hence customer service levels are significantly increased. The unnecessary inventory based on imprecise estimation of production requirements are minimized. Before the planning system is implemented, inventory levels for families, which have a production sequence given by the planners, were at a level such that they could cover demand for 7, 14 and 21 days for the products in second, third and forth families, respectively. Since family productions are optimized, those inventory levels are decreased to 7, 10 and 14 days, respectively, without facing any loss of sales due to product shortages. With the planning system, planners have an improved vision of bottlenecks in the capacity, so that, they can manage production such that they do not face any loss of sales. They can also advise the sales department by revising forecasts.

The company operates in a multi-facility production environment, where the product and material distribution among the production network is one of the key issues in terms of efficiency. The company reported a 35% decrease in their transportation costs within the production network after the planning system is implemented.

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. Integrating the capacity planning with shift planning improved the utilization of resources in the converting plants.

The operating environment of the company is highly competitive. It is not uncommon to face a drastic marketing move by one of the competitors each month. The planning system improved the responsiveness of the company to take correct position against such perturbations on the estimated state of the market. The improvement of responsiveness is provided by the capability of integrated planning system by supporting a wider vision on the system as a whole. The fact that the planning system accelerated the daily operations of planners has also an important effect. Preparing long term production plan at the beginning of each month and revising it during the month took hours for planners, where these operations take less than one hour with the planning system. Integration of planning system with ERP and PMS allows planners to have overview of shop floor so that they can detect errors and adjust them quickly.

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