INTEGRATED PRODUCTION PLANNING, SHIFT PLANNING AND DETAILED SCHEDULING IN A TISSUE PAPER MANUFACTURER

by

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ABSTRACT

INTEGRATED PRODUCTION PLANNING, SHIFT PLANNING AND DETAILED SCHEDULING IN A TISSUE PAPER MANUFACTURER

The thesis is about the implementation of an integrated planning system in a large tissue paper manufacturer in Turkey. The manufacturer operates over four production facilities in different geographical locations where two of the plants are owned by the company while the other plants are owned by two separate contractors. The manufacturing process is composed of two phases. In the first phase paper is produced as a bulk in the form of paper bobbins. In the second phase, bulk paper bobbins are converted into end products, like toilet papers, paper towels, napkins, etc. Although all plants are equipped to perform the converting operation, only one plant has a paper production facility. The company operates in an highly competitive market. Its products are fully substitutable by the products of its competitors. The company tries to fulfill customer demands through a number of sales channels. The main purpose of the company is to prevent loss of sales by continuous feed up of sales channels. Profit margins in the sector are very low. To be able to increase profits, company aims to decrease operational costs such as process, transportation, setup and inventory holding costs. In this thesis, we developed a planning system where main objectives are to decrease the operational costs, to increase customer service level and to increase responsiveness of planning department to fast changing conditions. The planning system is composed of three integrated models to solve the capacity planning, shift planning and scheduling problems. All three problems are solved by an mixture of optimization methods and heuristics. The planning system is implemented in ICRON Supply Chain Optimization System. Capacity planning and shift planning models have been in use since January 2011 and scheduling model has been in use since March 2011.

ÖZET

BİR TEMİZLİK KAĞIDI ÜRETİCİSİNDE BÜTÜNLEŞİK ÜRETİM PLANLAMA, VARDİYA PLANLAMA VE ÇİZELGELEME

Bu tez, Türkiye'deki büyük bir temizlik kağıdı üreticisinde bütünleşik üretim planlama, vardiya planlama ve çizelgeleme uygulaması üzerinedir. Üretici firma, farklı coğrafi bölgelerde bulunan üretim tesislerinde faaliyet göstermektedir. Bu tesislerden ikisi firmaya ait olup, diğer ikisi iki farklı anlaşmalı taşeron firmaya aittir. Üretim süreci iki fazdan oluşmaktadır. İlk fazda büyük kütlelerde kağıt üretimi gerçekleşmektedir. İkinci fazda bu kağıtlar, tuvalet kağıdı, kağıt havlu, mendil gibi son ürünlere dönüştürülmektedir. Tüm üretim tesisleri ikinci faz üretimi gerçekleştirecek ekipmana sahiptir. Buna karşın yalnızca bir tesiste kağıt üretimi gerçekleşebilmektedir. Kuruluş, yoğun rekabet ortamında faaliyet göstermektedir. Ürünleri, rakip firmaların ürünleri tarafından tümüyle ikame edilebilir ürünlerdir. Kuruluş müşteri taleplerini farklı satış kanallarıyla karşılamaya çalışmaktadır. Kuruluşun ana amacı, satış kanalları sürekli besleyerek satış kaybını önlemektir. Sektördeki kar marjları oldukça düşüktür. Karlılığı yükseltebilmek için, kuruluşun üretim, taşıma, kurulum ve envanter maaliyetleri gibi işletim maaliyetlerini düşürmesi gerekmektedir. Bu tezde, ana amacı işletim maaliyetleri düşürmek, müşteri servis seviyesini ve hızlı değişen koşullara karşı planlama departmanının tepki hızını artırmak olan bir planlama sistemi geliştirilmiştir. Planlama sistemi, kapasite planlama, vardiya planlama ve çizelgeleme problemlemlerini çözmek üzere, üç bütünleşik modelden oluşmaktadır. Tüm problemler, eniyileme yöntemleri ve sezgisel yöntemlerin birlikte kullanımıyla çözülmüştür. Planlama sistemi, ICRON Tedarik Zinciri Eniyileme Sistemi'nde uygulanmıştır. Kapasite planlama ve vardiya planlama modelleri Ocak 2011 itibariyle kullanımda olup, çizelgeleme modeli Mart 2011'de devreye alınmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

In this thesis 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.

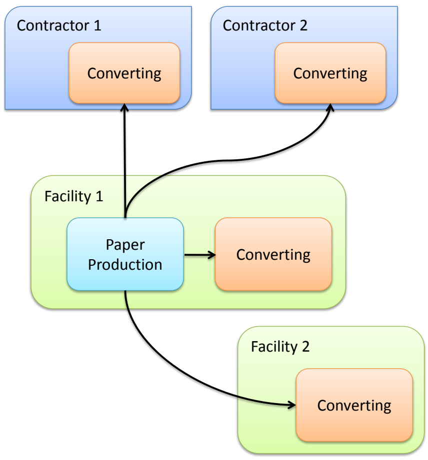


Figure 1.1. Manufacturing organization of the company.

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 1.1. 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:

- 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.

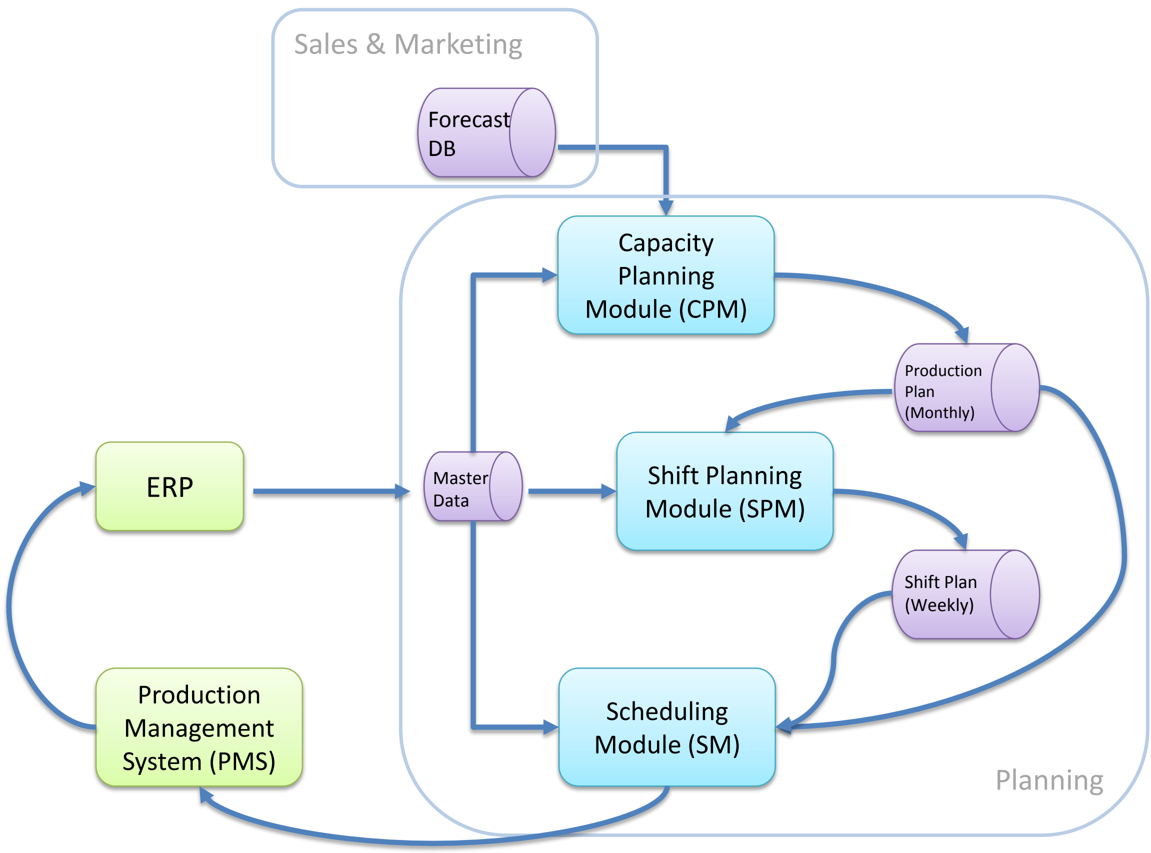


Figure 1.2. Integrated planning system architecture.

Architecture of the integrated planning system that we developed is shown in Figure 1.2. 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.

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 chapters is as follows: Chapter 2 provides an overview of the literature, where problems in this thesis are considered. In Chapter 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 Chapter 4, we define the planning problem as a whole and give definitions of three individual problems. Chapter 5 contains the descriptions of three models in detail. In Chapter 6 we give the details of implementation of three models. The integration of planning system with other systems is also explained in this chapter. Finally, in Chapter 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 [1] for a comprehensive treatment of production planning using mathematical programming methods. Mula *et al.* [2] 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.* [4] work on solving mixed integer programming (MIP) formulations of production planning problem, where fixed or setup costs are considered. Alain [3] proposes a primal-dual approach to solve capacitated production planning problem where fixed production costs are included. Since fixed costs are considered in the model, production planning problem is formulated as a MIP, where obtaining optimal solutions are only possible for very small instances. Akartunali *et al.* [4] deal with a heuristic approach to multi-level production planning where setups are considered in MIP model formulated for capacitated production planning problem. In the proposed heuristic approach, they combine *LP-and-fix* and *relax-and-fix* heuristics.

Fumero [5] and Jolayemi *et al.* [6] consider production planning problem on a network of production plants. Both studies formulate the problem as a MIP model. Fumero [5] uses Lagrangean relaxation methods to solve production planning problem where the manufacturing organization is distributed among a number of plants and size, production plant and resource of production lots sizes should be determined. Jolayemi *et al.* [6] determine the production requirements in all plants, whereas they also evaluate subcontracting needs in case of capacity shortages .

Kim and Kim [7] combine classical LP model with simulation to find a capacity-feasible production plan. The main concern of the study is that the production lead times are not necessarily in line with the time buckets of the LP model. To adjust the use of capacity they introduce new parameters called effective loading ratio and effective utilization factor to the capacity constraint of LP model. Those parameters are determined by the simulation, where the production plan generated by LP is used. Another study where lead times are considered in modeling approach is [8]. Here, the released production order at any time period can only be fulfilled after a certain amount of periods. Satisfaction of dependent demands and capacity usage constraints are modeled with respect to that fact.

Leung *et al.* [9] formulate a goal programming model for aggregate production planning problem in multi-facility production environment with limited storage and resource capacities, where goals are profit maximization, minimizing defect and repair costs and maximizing resource utilization. Fuzzy multi-objective linear programming approach for aggregate production planning problem is developed in [10]. Same authors work on development of possibilistic linear programming model for aggregate production planning problem in [11].

Another extension to production planning problem is provided by [12], where there exists flexibility in demand fulfillment. That is, from a number of demands for a time period, model may choose to satisfy only some portion of demands. The objective is to maximize profit where setup costs and inventory holding costs are taken into consideration. Authors achieve some results for the optimal solution of the problem such as in the optimal solution, no demand is partially satisfied and demands are not partially delivered.

Optimization methods have been used for shift planning in various industries. Ernst *et al.* [13] provide a review of staff scheduling problems of different kinds, application areas and methods. Azmat and Widmer [14] propose a three-step method to determine work loads of employees working on a shift, where legal constraints are also considered. Lagodimos and Leopoulos [15] develop an integer linear program for manpower shift planning problem in a food manufacturing company and proposes two greedy heuristics to solve the problem. Lagodimos and Mihiotis [16] propose policies regarding manpower and overttime planning for each workday with minimum cost in a packing shop. They use integer linear programming models to obtain optimal policies. In [17], employees are serving to customers in their places. The problem is to determine the number of employees which should be hired for each shift where the demand is changing during the day. The problem is formulated as a MIP model where every day is divided into periods and for each period average demands are calculated given the historical data. Also in [18] demand fluctuations are considered in workforce planning. They propose a mixed integer linear programming model where objectives are to minimize total employed workforce and to balance the workload among employees. An application in airline crew scheduling is presented in [19], where goal programming method is used. An application in healthcare area is given in [20], where the seniority levels of employees are different.

In our survey we focus on hybrid flow shop scheduling problems where optimization techniques are used. Mendez *et al.* [21] survey the use of optimization techniques for solving scheduling problems. Ruiz *et al.* [22] review studies on hybrid flow shop scheduling problem. In [23], an extensive review on scheduling problems with setup times is provided.

In [24], MIP models and heuristic approaches are proposed to model realistic scheduling problems in hybrid flow shops, where sequence-dependent setup times, machine eligibility and precedence constraints are considered. Another MIP formulation is proposed in [25] for a real life problem encountered in a manufacturing firm in electronic and semiconductor industry. A case study in electrical appliance manufacturer is presented in [26], where MIP models are used.

A MIP formulation is proposed in [27], where the objective is to maximize machine utilization and also to minimize tardiness and earliness penalties of orders. Sawik [28] provides a MIP model for flexible flow shops where intermediate buffer spaces are limited. Harjunkoski and Grossmann [29] combine MIP and constraint programming models to solve multi-stage scheduling problems. Using MIP, they first assign production batches to resources. Sequencing of batches are performed using constraint programming method. Prasad and Maravelias [30] develop a mixed integer programming model for manufacturers with batch processing. The model is composed of three decision stages: determining production batches, assigning batches to units and finally, sequencing batches assigned to each unit.

The problem studied in [31] is multi-product multi-stage scheduling problem in pharmaceutical industry. Authors propose two alternative MIP formulations and a solution approach for real life problems, where they decompose solution procedure into two steps, i.e. constructive and improvement steps. In constructive step, they schedule orders one by one using MIP model until each order is scheduled and a feasible solution is obtained. In improvement step, they re-order batches until no improvement is obtained. Mendez *et al.* [32] deal with multi-stage flow shop scheduling problem in batch facilities, where they propose a mixed integer linear programming formulation.

There are studies which combine production planning and planning of labor capacity. Aghezzaf [33] integrates aggregate production planning and labor capacity planning in a mixed integer linear programming model. Then he provides a decomposition scheme and a solution approach where production planning problem and labor capacity planning problems are solved iteratively.

Several studies have focused on designing integrated methods for solving production planning and scheduling problems (e.g., [34, 35, 36]). Bhatnagar *et al.* [37] 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 [39]. Authors first solve a linear programming model, where production quantities for each period are determined.

Given the production quantities and lot sizes (this is a parameter assumed to be given by the user) are given to scheduling module, where scheduling is performed based on a simulated annealing approach.

Relatively few researchers have considered the interaction between shift planning and production scheduling ([40, 41]). 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 chapter we first provide information about characteristics of competitive environment. Then we characterize the production environment and give the details regarding integration of planning system with other systems.

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 right positions against changing market conditions.

There are three sales channels: wholesale dealers, supermarket chains and export channel. Wholesale dealers are keeping their inventory at a certain level. When the inventory level decreases under a specified stock level, a replenishment order is generated and sent to the company. The operation of supermarket chains is different than wholesale dealers where they do not have an inventory of products. Usually the company owns the stocks located in supermarkets' inventory and/or shelf and also the costs incurred by inventory holding. In essence, the company is in the contact point with consumers. Here, not being on shelf means direct loss of customers. Export channel operates based on customer orders from different regions of Europe and Asia. To be able to satisfy the demands of different sales channels, the company tries to manage its production based on forecasts.

Prices of company's products are set by the market, which means that the profit cannot be controlled by increasing prices. Therefore the company can only increase its profit by decreasing its costs. Components of costs are mainly raw material acquisitions, operational costs like transportation, energy consumption, labor costs, inventory holding costs and setup costs. Since the company has no control on the purchasing costs, they can only decrease their operational costs. Hence, the operational costs such as transportation costs and inventory holding costs are mainly determining the profit margin.

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 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 (Figure 3.1).

Figure 3.1. Examples for different types of products.

In the paper production phase, chemical compounds of the paper are mixed in huge containers. The mixture runs through the line where it is dried and flattened to the required thickness of the tissue paper. The resulting thin paper is coiled up to obtain paper bobbins whose weight differ from 0.5 up to 4 tons depending of 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.

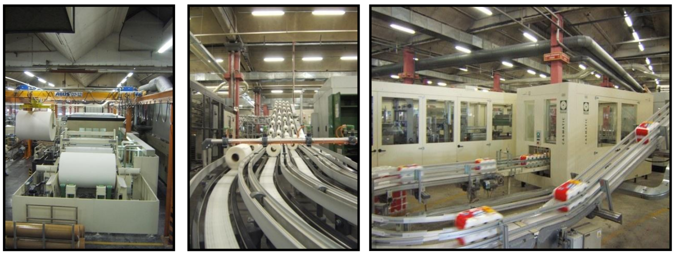
Paper production is performed on large dedicated machines (Figure 3.2), where one paper can be produced in more than one machine. Because of the chemical processes during paper production, product changes on paper machines necessitate significant setups. That is, the chemicals in the large mixing container should be removed such that they do not get mixed with the chemicals of the next product and whereby the nature of consequent product is not harmed. Those setups require long durations, workforce and high energy consumption.

(a) (b)

Figure 3.2. Final stage of a paper machine: Thin paper is coiled up, (a), and paper bobbins are obtained.

The second phase is called the "converting" phase. In this phase paper bobbins are loaded on "converting" machines where the paper is cut into required sizes and packaged (Figure 3.3). Each converting machine is composed of one single line where no interruptions between cutting and packaging operations exist.

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 machines, where cylindrical products



(a) (b) (c)

Figure 3.3. Example for a converting line: (a) Paper bobbins are loaded on converting machine, (b) they are cut into required sizes, (c) and at the end, they are packaged.

are produced, tissue machines, napkin machines and facial tissue machines. Figure 3.3 shows an example for toilet paper machine.

3.2.2. Multi-facility Production System

The manufacturing organization of the company is given in Figure 1.1. The company owns two production plants in different geographical locations. The company has also agreements with two contractors on the capacity which will be used for production requirements of the company. 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 divided into families. The concerns in family compositions are different for papers and finished products.

<u>3.2.3.1. Paper Families.</u> As stated in Section 3.2.1, paper production contains chemical processes and production changes require costly setups, where chemicals of last production should be removed from the container where the chemical ingredients of paper are mixed. To eliminate those costly setups paper production turned into 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. Quality level of the paper increase with the increase in the level of softness and durability of paper. 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, the planners pay very much attention on successive paper productions on the same resource. The concern is that the papers having similar ingredients should be produced in series. For this reason, papers are divided into families with respect to the similarity of their chemical compounds. Sixty 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.

3.2.3.2. 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 production requirements of products in such a family are satisfied during the production period of that family. For some product families planners want to force the production to continue at least for a minimum amount of time, which is the minimum production duration defined for that family. Planners determine a fixed production sequence for some families on some resources during a month. Here, the aim is to ensure minimum setup time spent on those resources.

3.3. Performance Indicators

There are a number of performance indicators, which mainly lead the decision making activities of planning department. In fact, the main objective is to increase profit. Increase in profit can be obtained by lowering the costs through planning activities.

The most important issue in planning activities is to keep customer satisfaction at the highest level. That is, the probability of being stock-out in any product must be kept as low as possible.

The production of company's products is performed in large volumes, which leads in high inventory levels. The inventory levels should be right quantities such that the inventory holding costs and at the same time the probability of being stock-out are low.

That means, the company should keep inventory for “right” items in “right” quantities.

Since profit margins are limited, operational costs such as transportation, process and overhead costs, i.e. energy consumption costs, should be low. Also costs induced by setups are important factors in total operational cost. Since setups lead to loss of energy, time and also labor force, they should be minimized.

4. PROBLEM DEFINITION

4.1. Basic Definitions

This section consists of basic definitions which will be used in following sections.

Let I be the set of *part*s, where every tangible item in the production system, such as raw materials, finished and semi-finished goods, is called a *part*. Let $i \in I$ be the index of a part. Let F, S and M be disjoint subsets of I, where $F \cup S \cup M = I$. If a part i is in F, then it is a finished good which is a result of the converting phase. Similarly if a part i is in S, then it is a semi-finished good, i.e. a bulk paper. Parts in M are raw materials, which can be used either in the paper production or the converting phase.

Let G be the set of all part families and let g the index of a part family. Let χ_{ig} be a parameter indicating whether part i is a member of family g:

$$\chi_{ig} = \begin{cases} 1 & \text{if part family } g \text{ contains part } i \\ 0 & \text{otherwise} \end{cases}$$

Part families do not have to be disjoint or mutually exclusive. Suppose that there are two part families g_1 and g_2. If for all i such that $\chi_{i,g_1} = 1$, $\chi_{i,g_2} = 1$ is also true, then this means that all parts in g_1 are also a member of g_2.

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. Let P be the set of all processes and P_i be the set of processes whereby part i can be provided, i.e. produced or purchased, where $|P_i| \geq 1$ for any part $i \in I$. 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.

Let R be the set of all resources, and let R_s and R_f indicate the set of paper machines and set of converting lines, respectively. 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.

Let K be the set of inventory locations and let K_i be the set of inventory locations where part i can be placed. 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.

The objective in planning activities is to satisfy demand on products which originate from a number of sales channels. A customer order from any sales channel is called a *requirement*. Let R_{iu}^q be the quantity of uth requirement for part i of type q, where $i \in F$. Customer orders from different sales channels have different priorities. Here, index q stands for the type of sales channel and so it is the indicator of requirement's priority. Let Q be the set of all requirement types. And let d_{iu}^q be the due date of the uth requirement for part i.

4.2. Planning Problem

There are various decisions which have to be taken by the planners for short-term and long-term planning horizons.

Sales department generates forecasts for the sales of the next four months. Given those forecasts, capacity allocations among all production plants should be determined by the planning department. Those long-term decisions include determination of finished and semi-finished part production requirements for every resource and material requirements for each month. 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.

For the long-term planning horizon also the labor force requirements should be determined. That is, due to capacity requirements, planning department should decide on the shift plan for each resource, whereas the rules and regulations negotiated with the labor union should be obeyed.

In the short term, the daily schedule for every resource should be determined. Here, the following questions have to be answered: "which product should be produced?", "how many items should be produced?" and "when should the production of the batch start?"

4.3. Architecture

We decomposed the problem into three separate problems, see Figure 4.1: capacity planning, shift planning and scheduling. The problems are connected to each other by input-output relations.

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 are determined. Based on those monthly production requirements, weekly shift plan of each resource should be determined. Maintenance schedule and restrictions by labor law are further inputs of shift planning 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.

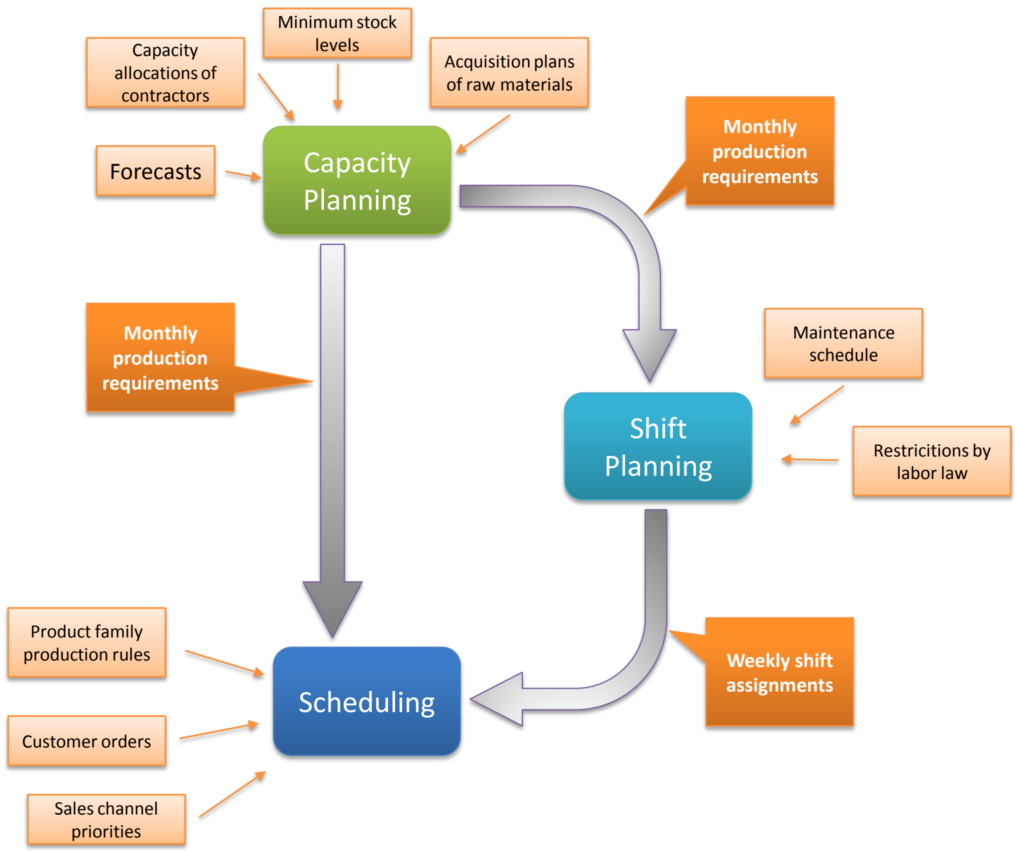


Figure 4.1. Architecture of planning problem.

4.3.1. Capacity Planning Problem

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.

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 $t = 1, 2, \ldots, |T|$. Every $t \in T$ represents a period which has a length of one month. Sales department is able to forecast the demand of the next four months in advance, that is for our case $|T|$ equals to four.

Monthly production and procurement requirements are the main decision variables of our model. Let x_{ipt} be 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. For this purpose, let y_{iklt} be 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 $t \in T$.

Let ID_{it} be 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. Let DD_{it} be 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 capacities on that resources. We call those installed capacities *regular* capacity and denote it by the parameter RC_{rt}, i.e. regular capacity in seconds of resource r in period t, where $r \in R$ and $t \in T$. 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. In Section 6.1, we provide the details about determination of regular and additional capacities. Let rcu_{rt} and ocu_{rt}

be the regular capacity usage and additional capacity usage amounts, respectively, where, $r \in R$ and $t \in T$.

4.3.1.1. Planning Issues. There are a number of planning issues which have different sources such as technological limitations and strategic decisions of planning and sales departments.

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 which 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 4.2 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 $t + 1$.

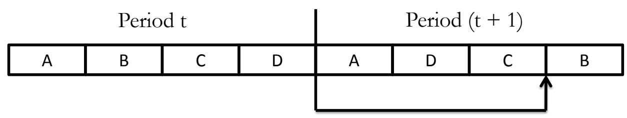


Figure 4.2. An example for the production sequence of product families.

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.*

One 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.

Capacity planning problem generates the inventory levels, production and transshipment quantities optimally by solving an LP model, where all issues explained above are taken into consideration.

4.3.2. Shift Planning Problem

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 4.1 shows the working hours and days of all shift types.

Table 4.1. 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 4.2).

Table 4.2. 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 $w = 1, 2, \dots, |W|$. 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.

4.3.2.1. Planning Issues. Shift planning problem contains several 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 capacity requirements, monthly capacity usages, 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. That is, if full shift, i.e. 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: *Continuously 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. Consider the shift plan in Figure 4.5, where at the end of each week the shift of the resource is changed.

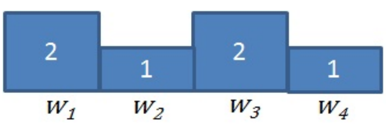


Figure 4.3. An example for undesired shift plan.

The same capacity level as in Figure 4.5 can be obtained by the shift assignment shown in Figure 4.6. Here, the only change occurs at the end of the week w_2.

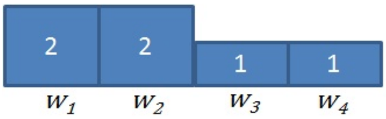


Figure 4.4. An example for desired shift plan.

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

Consider the shift plan shown in Figure 4.5, where the Issue 8 is not taken into account. Here, total amount of shift change is 4. When Issue 8 is considered, the shift plan shown in Figure 4.6 is obtained, where it is ensured that the shift assignments attain the same capacity level as in Figure 4.5. Here, the total amount of shift change is decreased to 2.

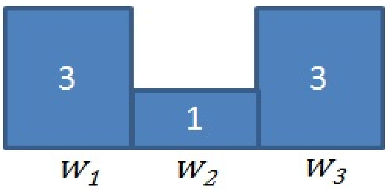


Figure 4.5. An example for undesired shift plan where Issue 8 is violated.

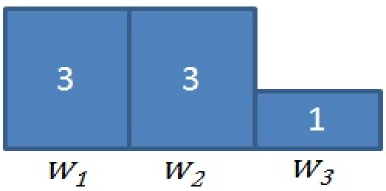


Figure 4.6. An example for undesired shift plan where Issue 9 is violated.

Issue 9 states that there should not be drastic shift changes between the weeks. For the example in Figure 4.6, the shift plan should be as in Figure 4.7.

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.

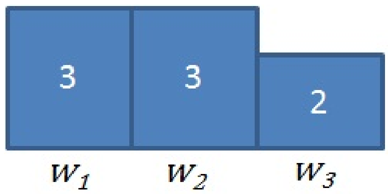


Figure 4.7. An example for desired shift plan.

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 considering several reasons such as lack of labor, limits on energy consumption or agreements with labor union.

Shift planning problem is defined as to find the optimum shift plan for every resource such that the above issues are considered.

4.3.3. Scheduling Problem

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. The output of scheduling problem 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.

There are different types of requirements for finished parts which can be satisfied by the production batches. We define $R_i^{[j]}$ as the set of satisfied requirements by the production batch $B_{ip}^{[j]}$. Our aim is to generate a schedule, where all requirements are satisfied on time.

The requirements for paper production are generated by the needs of converting phase. There is a lag between the time that paper bobbin is produced and the time that the bobbin is ready to use in converting phase. Since paper production is performed only in one plant, the paper requirements of other facilities are supplied from that plant. Since facilities are located in different geographical regions, transportation of paper bobbins from the plant of paper production to the others takes up to 2 days. That is, there exists another time lag until a paper bobbin is ready to use in another facility.

There are some predefined constraints on quantities of production batches for both finished and semi-finished parts. One of them is the minimum lot constraint. Let μ_i be the minimum lot quantity for part i, where $i \in S \cup F$.

As stated in Section 3.2.3, there exist part families which have different scheduling constraints. We can cluster the part families based on their scheduling requirements as follows: families whose production should take place only once in a month (see Issue 14), families with minimum production duration restriction (see Issue 15), semi-finished part families (see Issue 17).

4.3.3.1. Planning Issues. Similar to capacity planning and shift planning problems, scheduling problem include several 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. The aim is 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. In CP model monthly production requirements are determined based on resources. Since the capacity allocation decisions are taken in CP level, scheduling results should comply with the production decisions of CP model.

There exist a number of planning issues regarding part families in scheduling level, most of which are not considered in CP level. These issues are important in scheduling level since the constraints related with them become relevant in the short term even though they are negligible at CP level.

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. Here again, the aim is to decrease setup requirements.

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

In Issue 4 of CP model (Section 5.1.1) 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.*

As mentioned in Section 3.2.3 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.

5. SOLUTION PROCEDURES

Considering the architecture in Figure 4.1 we constructed three models for three problems defined in Section 4.3: capacity planning (Section 5.1), shift planning (Section 5.2) and scheduling (Section 5.3) models.

5.1. Capacity Planning Model

Capacity planning model (CPM) is a linear programming (LP) model aims to generate an optimal production and contracting plan for the given medium-term planning horizon. The main decision variables are given in Section 4.3.1, which are inventory levels at the end of each month, monthly production, procurement and transshipment quantities and resource usages. The constraints of the model are explained in detail in Section 5.1.1, the cost function and the optimization model are given in Sections 5.1.2 and 5.1.3, respectively.

5.1.1. Constraints

First set of constraints is the set of inventory balance equations for finished, semi-finished goods and raw materials. Equations 5.1 show the inventory balance equations for finished goods. The independent demand ID_{it}, i.e. the forecast for part i in period t, the amount in inventory k at the end of the period t, i.e. I_{ikt}, and the transshipped quantity of part i from inventory k to other inventory locations, i.e. y_{iklt}'s, are equal to the sum of production amount in period t, i.e. x_{ipt}'s, amount of part i in inventory k at the beginning of period t and the transshipment amount from other inventory locations to inventory k. In this problem, transportation and production lead times are less than a month. Hence, in CP model lead times are assumed to be zero.

$$I_{ik,t-1} + \sum_{p \in P_i(k)} x_{ipt} + \sum_{l \in K_i \setminus \{k\}} y_{ilkt} - \sum_{l \in K_i \setminus \{k\}} y_{iklt} - ID_{it} = I_{ikt} \tag{5.1}$$

$$\forall i \in F, \forall k \in K_i \text{ and } \forall t \in T$$

Similarly, the inventory balance equations for semi-finished and raw materials are shown in Equation 5.2. The demands on semi-finished products and raw materials are called dependent demand, since they depend on the production decisions on finished and semi-finished products. Here again, lead times are assumed to be zero.

$$I_{ik,t-1} + \sum_{p \in P_i(k)} x_{ipt} + \sum_{l \in K \setminus \{k\}} y_{ilkt} - \sum_{l \in K \setminus \{k\}} y_{iklt} - DD_{it} = I_{ikt} \tag{5.2}$$

$$\forall i \in S \cup M, \forall k \in K_i \text{ and } \forall t \in T$$

DD_{it}'s in Equations 5.2 are also decision variables, which are determined by the Equations 5.3 and 5.4. Equations 5.3 determine the raw material requirements of finished and semi-finished parts and Equations 5.4 determine the 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. Note that, u_{ipj} is zero if part i does not require part j in process p.

$$\sum_{i \in F \cup S} \sum_{p \in P_i} u_{ipj}\, x_{ipt} = DD_{jt} \quad \forall j \in M \text{ and } \forall t \in T \tag{5.3}$$

$$\sum_{i \in F} \sum_{p \in P_i} u_{ipj}\, x_{ipt} = DD_{jt} \quad \forall j \in S \text{ and } \forall t \in T \tag{5.4}$$

Equations 5.5 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. Processing times are given in seconds. Note that, $P_i(r) = \emptyset$, if part i does not have a process which uses resource r.

$$\sum_{i\in F\cup S}\sum_{p\in P_i(r)} w_{ipr}\, x_{ipt} = rcu_{rt} + ocu_{rt} + ofcu_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{5.5}$$

$$rcu_{rt} \leq RC_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{5.6}$$

$$ocu_{rt} \leq OC_{rt} \quad \forall r \in R \text{ and } \forall t \in T \tag{5.7}$$

The variables $ofcu_{rt}$ in Constraints 5.5 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 5.6 and 5.7 set upper bounds to resource usages. That is, regular resource usage is bounded by the total regular capacity and additional capacity usage is bounded by the total additional capacity of the resource.

In the rest of this section, explained constraints are related with a planning issue given in Section 4.3.1.1.

To handle Issue 1, i.e. defining minimum ending inventory levels for some parts, planners decide on a parameter called δ_{ikt} for part i, inventory location k and period t. This parameter indicates the number of days whose demand should be covered by the inventory at the beginning of period $t+1$. Let s_{ikt} be the minimum inventory level for part i in inventory location k at the end of period t. Here, the assumption is that the demand is constant during the month.

Let N_t be the number of days in period t. If $i \in F$, s_{ikt} is calculated as follows for $t = 1, 2, \ldots, |T| - 1$:

$$s_{ikt} = \frac{\delta_{ikt}\ ID_{i,t+1}}{N_{t+1}}$$

If $i \in S$, the calculation is as follows:

$$s_{ikt} = \frac{\delta_{ikt}\ DD_{i,t+1}}{N_{t+1}}$$

For $t = |T|$, it is assumed that the demand for the period $|T| + 1$ is going to be the same as the demand in period $|T|$. For $s_{ik,|T|}$ we have the following formulations:

$$s_{ik,|T|} = \frac{\delta_{ik,|T|}\ ID_{i,|T|}}{N_{|T|}} \text{ where } i \in F$$

$$s_{ik,|T|} = \frac{\delta_{ik,|T|}\ DD_{i,|T|}}{N_{|T|}} \text{ where } i \in S$$

Constraints 5.8 which handles Issue 1 also allows the planners to reflect their experience on the generated plan, where they can estimate possible future fluctuations on demand, which are not reflected on the official forecasts.

$$I_{ikt} \geq s_{ikt} \quad \forall i \in F \cup S,\ k \in K_i \text{ and } \forall t \in T \tag{5.8}$$

Issue 2 states the contractor agreements on capacity allocations. The contractors are responsible of production of certain finished parts. The capacity of contractor's plant allocated regarding the agreements are distributed among those parts. The distribution is achieved by minimum production decision taken by the planners. Let z_{ipt} be the minimum production quantity determined by the planners for part i through process p in period t, where $i \in F$ and $p \in P_i$ and $t \in T$.

$$x_{ipt} \geq z_{ipt} \quad \forall i \in F,\ \forall p \in P_i \text{ and } \forall t \in T \tag{5.9}$$

Issue 3 indicates that there are production orders released to shop floor. Since those productions are fixed, they must be included in the monthly production plan. Let o_{ip} be the production order quantity of part i through process p, where $i \in F \cup S$ and $p \in P_i$. Constraints 5.10 set the production order quantity as a lower bound for the production in first period. Note that, no production orders are released for periods other than the first period.

$$x_{ip,1} \geq o_{ip} \quad \forall i \in S \cup F \text{ and } \forall p \in P_i \tag{5.10}$$

Issue 4 is about production sequence given for a number of product families on a resource. Let n be the number of part families for which a sequence on a resource is given. Let $\gamma(g, r, t)$ indicate the sequence of part family g on resource r in period t, where $\gamma(g, r, t)$ may have values from 1 to n. And let R^* be the set of resources for which a family sequence is given.

Let α_{ikt} be 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 $t+1$. Here again, the assumption is that demand is constant during the period. α_{ikt} is calculated as follows: Let the sequence of family g^*, to which part i belongs, be γ^* in period $t+1$ on resource r such that $\gamma^* > 1$. Let λ be the number of days in period $t+1$ until the production of family g^* starts in period $t+1$. The production time of parts in families which will be produced before family g^* is given by

$$\sum_{g:\ \gamma(g,r,t+1)<\gamma^*} \sum_{i \in F} \sum_{p \in P_i(r)} \chi_{ig}\ x_{ip,t+1}\ w_{ipr}.$$

After the conversion into days, we get

$$\lambda = \sum_{g:\ \gamma(g,r,t+1)<\gamma^*} \sum_{i \in F} \sum_{p \in P_i(r)} \chi_{ig}\ x_{ip,t+1}\ w_{ipr}\ \frac{1}{60 * 60}.$$

So, α_{ikt} is given by

$$\alpha_{ikt} = \frac{\lambda\, ID_{i,t+1}}{N_{t+1}}.$$

For $t = |T|$, we have

$$\alpha_{ik,|T|} = \frac{\lambda\, ID_{i,|T|}}{N_{|T|}}.$$

Note that, $P_i(r) = P_i(k)$, i.e. part i is located in inventory k after it is produced on resource r. Constraints 5.11 are written for every part i which belongs to a part family with a given production sequence.

$$I_{ikt} \geq \alpha_{ikt} \quad \forall i \text{ such that } \chi_{ig} = 1 \text{ and } \gamma(g, r, t) \text{ exists, } \forall r \in R^* \text{ and } \forall t \in T \qquad (5.11)$$

5.1.2. Cost Function

The cost function consists of production, purchasing, resource usage, and inventory holding costs.

Let c_{ip} be the unit cost of part i provided by process p, where $i \in I$ and $p \in P_i$. And let C be the total production and procurement costs and it is given by

$$C = \sum_{i \in I} \sum_{p \in P_i} \sum_{t \in T} c_{ip}\, x_{ipt}$$

Inventory holding cost parameter is h_{ik}, i.e. cost of holding one unit of part i in location k, where $i \in I$ and $k \in K_i$. And let H be the total inventory holding cost.

$$H = \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} h_{ik}\, I_{ikt}$$

Let f_{ikl} be the freight cost for one unit of part i transshipped from location k to location l, where $i \in I$ and $k, l \in K_i$. Let F indicate the total freight cost.

$$F = \sum_{i \in I} \sum_{k \in K} \sum_{l \in K \setminus \{k\}} \sum_{t \in T} f_{ikl}\, y_{iklt}$$

Regular capacity and additional capacity usage costs are given by rc_r and oc_r, respectively, where $r \in R$. We also have the cost of using overflow capacity, i.e. ofc_r, where $r \in R$. Let U be the total resource usage cost. Note that, $rc_r < oc_r \ll ofc_r$ for every $r \in R$.

$$U = \sum_{r \in R} \sum_{t \in T} rc_r\, rcu_{rt} + \sum_{r \in R} \sum_{t \in T} oc_r\, ocu_{rt} + \sum_{r \in R} \sum_{t \in T} ofc_r\, ofcu_{rt}$$

Hence, cost function Z is given as follows:

$$Z_{CP} = C + H + F + U \tag{5.12}$$

Cost parameters of cost function are determined based on a normalization and prioritization scheme. Since the variables like inventory level, production quantity and capacity usage have different unit of measures, we need a normalization to be able to obtain comparable cost components. Our normalization is based on conversion of every term into time units. Which means, c_{ip}'s, h_{ik}'s and f_{ikl}'s are calculated using unit processing times, i.e. w_{ipr}. Second factor which determines those parameters is the prioritizations among cost components which should be defined by the planners. For instance, planners should have a preference between using additional capacity on a resource and having more inventory. We denote the priorities among different cost parameters as π_x where x stands for the related cost component. Cost parameters are calculated as follows:

$$c_{ip} = w_{ip,r(p)} * \pi_c * \alpha_{ip} \quad \forall i \in F \cup S \text{ and } \forall p \in P_i$$

where π_c is the priority multiplier for process costs and α_{ip} is the priority multiplier among alternative processes of part i (see Issue 5). For inventory holding cost parameter we have the following:

$$h_{ik} = \frac{\sum_{p \in P_i(k)} w_{ip,r(p)}}{|P_i(k)|} * \pi_h \quad \forall i \in F \cup S \text{ and } \forall k \in K_i$$

where π_h is the priority multiplier for inventory holding costs, which we multiply with the average unit processing time of processes related with inventory location k. Similarly, for freight cost parameters we make the following calculations:

$$f_{ikl} = \frac{\sum_{p \in P_i(k)} w_{ip,r(p)}}{|P_i(k)|} * \pi_f \quad \forall i \in F \cup S \text{ and } \forall k, l \in K_i$$

where π_f is the priority multiplier for freight costs, which we multiply with the average unit processing time of processes related with inventory location k. For resource usage costs we have three cost parameters:

$$rc_r = \pi_u \quad \forall r \in R$$

$$oc_r = \pi_u * \alpha_o \quad \forall r \in R$$

$$ofc_r = \pi_u * \alpha_{of} \quad \forall r \in R$$

where π_u is the priority multiplier for resource usages. Note that, since capacity usages are already in time units, we do not have processing times as multipliers. Here, α_o and α_{of} are positive multipliers for additional capacity and overflow capacity usages, respectively, where $\alpha_o \ll \alpha_{of}$. Also note that, overflow capacity usage cost parameter has the biggest value among all cost components, since overflow usages should not have positive quantities unless the model contains an infeasibility.

5.1.3. Model

Capacity planning model is an LP model as given below. The objective of CP model is to minimize total cost, subject to the constraints given in Section 5.1.3 and nonnegativity constraints given below.

$$\textbf{CP}: \ \min \quad Z_{CP}$$

subject to 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 5.9, 5.10, 5.11
where

$$x_{ipt} \geq 0 \qquad \forall i \in I,\ \forall p \in P_i \text{ and } \forall t \in T \tag{5.13}$$

$$I_{ikt} \geq 0 \qquad \forall i \in I,\ \forall k \in K \text{ and } \forall t \in T \tag{5.14}$$

$$y_{iklt} \geq 0 \qquad \forall i \in I,\ \forall k,\ l \in K \text{ and } \forall t \in T \tag{5.15}$$

$$DD_{it} \geq 0 \qquad \forall i \in S \cup M \text{ and } \forall t \in T \tag{5.16}$$

$$rcu_{rt},\ ocu_{rt},\ ofcu_{rt} \geq 0 \qquad \forall r \in R \text{ and } \forall t \in T \tag{5.17}$$

Total number of decision variables in CP model can be calculated as follows:

- Production quantity variables (5.13): $|I| \times |P| \times |T|$
- Ending inventory variables (5.14): $|I| \times |K| \times |T|$
- Transshipment quantity variables (5.15): $|I| \times |K|^2 \times |T|$
- Dependent demand variables (5.16): $|S \cup M| \times |T|$
- Resource usage variables (5.17): $3 \times |R| \times |T|$

Total number of decision variables is given by $|T| \times (3 \times |R| + |I| \times (|P| + |K| + |K|^2) + |S \cup M|)$. Sizes of all constraints in CP model are listed below. These calculations give the possible maximum number of constraints:

- Inventory balance equations (5.1 and 5.2): $|I| \times |K| \times |T|$
- Dependent demand equations (5.3 and 5.4): $|S \cup M| \times |T|$
- Resource usage and capacity constraints (5.5, 5.6 and 5.7): $3 \times |R| \times |T|$
- Minimum inventory constraints (5.8): $|F \cup S| \times |K| \times |T|$
- Minimum production constraints (5.9): $|F| \times |P| \times |T|$
- Open production order constraints (5.10): $|S \cup F| \times |P|$
- Product family constraints (5.11): $|G| \times |R| \times |T|$

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 aim of shift planning model (SPM) is to generate weekly shift assignments for all resources. We construct a mixed-integer programming (MIP) model for each resource. Main decision variables of our model represent the shift plan assigned to the resource for each week.

$$y_{rsw} = \begin{cases} 1 & \text{if shift } s \text{ is assigned to resource } r \text{ for week } w \\ 0 & \text{otherwise} \end{cases}$$

where $s \in S$, $w \in W$ and $r \in R$.

Since shift assignments of different resources are independent of each other, we construct a separate MIP model for every resource. Hence, we redefine y_{rsw} such that

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

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

5.2.1. Constraints

In this section, we will define the constraints of MIP model which is constructed for one resource. Let r^* be the resource for which the model constraints are described.

Constraints 5.18 state that for each week w there can only be one shift assignment s on resource r^*.

$$\sum_{s \in S} y_{sw} = 1, \quad \forall w \in W \tag{5.18}$$

As indicated in Issue 6, the shift assignments must cover the monthly capacity requirements determined by the CPM. The monthly capacity requirements of resource r^* is given by the sum of variables rcu_{r^*t} and ocu_{r^*t} for all $t \in T$. Remember that the resource usages are calculated in seconds.

$$\sum_{w \in W_t} \sum_{s \in S} h_s \, d_{swt} \, y_{sw} - \omega_w * 24 \geq (rcu_{r^*t} + ocu_{r^*t}) \frac{1}{60 * 60}, \quad \forall t \in T \tag{5.19}$$

Given D_{wt} for every $w \in W$ and $t \in T$, we determine the number of days which will be operated for a shift type s in week w of period t. Let this be a new parameter d_{swt}, for which the inequality $d_{swt} \leq d_s$ holds for each $s \in S$, $w \in W$ and $t \in T$. 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.

To be able to calculate the capacity loss due to Issue 7, we define a new binary variable indicating that a shift change is occurred from shift type 4:

$$\omega_w = \begin{cases} 1 & \text{if shift type 4 is assigned to week } w \\ & \text{and another shift type is assigned to week } w+1 \\ 0 & \text{otherwise} \end{cases}$$

where $w \in W \backslash \{|W|\}$. Constraints 5.20 set the value of ω_w to 1, if shift type 4 is assigned to week w, i.e. $y_{4w} = 1$, and another shift type $s \in S \backslash \{4\}$ is assigned to week $w+1$.

$$y_{4w} + y_{s,w+1} \leq \omega_w + 1, \quad \forall w \in W \backslash \{|W|\} \text{ and } \forall s \in S \backslash \{4\} \tag{5.20}$$

As mentioned in Issue 8, there may be alternative shift assignments which satisfy the Constraint 5.19. We define a new variable β_w which controls the change in shift assignments between consecutive weeks. Here, g_s is an integer for the type of shift s and is formulated as $g_s = |s|$ for all $s \in S$. β_w is a nonnegative variable and it will have a positive when the shift assignment is changed. One of our objectives is to keep the amount of this changes as low as possible.(see Section 5.2.2)

$$\sum_{s \in S} g_s\, y_{sw} - \sum_{s' \in S} g_{s'}\, y_{s',w-1} \leq \beta_w, \quad \forall w \in W \backslash \{1\} \tag{5.21}$$

$$\sum_{s' \in S} g_{s'}\, y_{s',w-1} - \sum_{s \in S} g_s\, y_{sw} \leq \beta_w, \quad \forall w \in W \backslash \{1\} \tag{5.22}$$

Based on Issue 9, we define Constraints 5.23 and 5.24. Here, it is ensured that the shift type changes between successive weeks do not exceed 1.

$$\sum_{s\in S} g_s\, y_{sw} - \sum_{s'\in S} g_{s'}\, y_{s',w-1} \leq 1, \quad \forall w \in W\backslash\{1\} \tag{5.23}$$

$$\sum_{s\in S} g_s\, y_{sw} - \sum_{s'\in S} g_{s'}\, y_{s',w-1} \leq 1, \quad \forall w \in W\backslash\{1\} \tag{5.24}$$

Shift assignments of first week cannot be changed as stated in Issue 10. Let ψ be the shift assigned on resource r^*, where $\psi \in S$. The following constraint sets the shift assignment of the first week.

$$y_{\psi 1} = 1 \tag{5.25}$$

Issue 11 mentions that planners may fix some shift assignments throughout the planning horizon. Those assignments are taken as input to the MIP model. Let γ_w be the assigned shift for week w, $\gamma_w \in S$. Constraints 5.26 assign y_{sw} variables to one for the fixed weeks. Let W' indicate weeks whose shift assignment is fixed.

$$y_{\gamma_w w} = 1, \quad \forall w \in W' \tag{5.26}$$

5.2.2. Cost Function

In our model, the components of cost function are total working hours and total number of shift changes.

Let WH_t indicate the total working hours in period t, where $t \in T$. For any period t, we can calculate WH_t as follows:

$$WH_t = \sum_{w \in W_t} \sum_{s \in S} h_s \, d_{swt} \, y_{sw}$$

Let B be the cost of shift changes, which is given by

$$B = \sum_{w \in W} \beta_w .$$

Cost function of shift planning model Z_{SP} is formulated as follows:

$$Z_{SP} = \sum_{t \in T} WH_t + B$$

5.2.3. Model

Subject to the constraints explained in Section 5.2.1, our model's objective function minimizes the total number of working hours and the total number of shift plan changes in consecutive weeks. Hence, the aim of our model is to generate a shift plan with minimum changes and that satisfies the capacity requirements of production resources with minimum working hours. SP model runs for every resource $r^* \in R$.

$$\textbf{SP}(r*): \ \min \ \ Z_{SP}$$

subject to 5.18, 5.19, 5.20, 5.21, 5.22, 5.23, 5.24, 5.25, 5.26
where

$$y_{sw} \in \{0, 1\} \qquad \forall s \in S \text{ and } \forall w \in W \tag{5.27}$$

$$\omega_w \in \{0,1\} \quad \text{where } w = 1,2,\ldots,|W|-1 \tag{5.28}$$

$$\beta_w \ \geq 0 \quad \forall w \in W \tag{5.29}$$

The number of decision variables can be calculated as follows:

- Shift assignment variables (5.27): $|S| \times |W|$
- Variables which detect the shift type changes (5.28): $|W| - 1$
- Shift change penalty variables (5.29): $|W|$

Total number of decision variables is given by $|W| \times (2+|S|)-1$, where $|W| \times (1+|S|)-1$ of them are binary variables. The number of constraints can be calculated as follows:

- Shift assignment constraints (5.18): $|W|$
- Capacity constraints (5.19): $|T|$
- Constraints which detect the shift type changes (5.20): $(|W| - 1) \times (|S| - 1)$
- Constraints which controls the shift assignments is consecutive weeks (5.21, 5.22, 5.23 and 5.24): $4 \times (|W| - 1)$
- First week constraint (5.25): 1
- Constraints for fixed weeks (5.26): $|W|$

In real life, 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 defined in Section 4.3.3 cannot be solved using simple dispatching heuristics, where a number of scheduling constraints should be considered at the same time. Scheduling model (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 (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 $b \in B$.

As indicated in Section 4.1, 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 does not only include customer orders of different sales channels. They also cover the forecasts given by the sales department. For this model, monthly forecasts are evenly distributed among periods in B. We define ID^q_{ib} as the demand for part i in period t of type q. Following calculation is done for all requirement types other than forecasts:

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

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. To be able to control different requirement satisfactions we define additional decision variables.

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 $b \in B$.

The major constraints of the batch sizing model are inventory balance equations, resource capacity, minimum production lot size and sequencing constraints for part families.

There exists an inventory balance equation for every requirement type q.

$$I^q_{i,b-1} + x^q_{ib} - ID^q_{ib} + U^q_{ib} - U^q_{i,b-1} = I^q_{ib} \quad \forall q \in Q, \forall i \in F \text{ and } \forall b \in B \tag{5.30}$$

Initial inventory is distributed among different inventories in Constraint 5.31.

$$I_{i,0} = \sum_q I^q_{i,0} \quad \forall i \in F \tag{5.31}$$

The following constraints ensure that the produced parts are distributed among production requirements of different types.

$$\sum_{p \in P_i} x_{ipb} = \sum_{q \in Q} x_{ib}^q \quad \forall i \in F \text{ and } \forall b \in B \tag{5.32}$$

Demand for semi-finished parts, i.e. for papers, are generated by the needs of converting phase. We define DD_{ib} as the dependent demand for part $i \in S$ and period $b \in B$. Here, b_{ipj} indicates the quantity of part j used by part i in process p.

$$\sum_{i \in F} \sum_{p \in P_i} b_{ipj}\, x_{ipb} = DD_{jb} \quad \forall j \in S \text{ and } b \in B \tag{5.33}$$

Since paper production is performed in one plant, we also need to specify transshipment quantities. Let z_{iklb} be the transshipment quantity of part i from inventory location k to inventory location l in period b, where $i \in S$, $k, l \in K_i$ and $b \in B$. Inventory balance equations for semi-finished parts are given in Constraints 5.34.

$$I_{ik,b-1} + \sum_{p \in P_i(k)} x_{ipb} + \sum_{l \in K \setminus \{k\}} z_{ilkb} - \sum_{l \in K \setminus \{k\}} z_{iklb} - DD_{ib} = I_{ikb} \quad \forall j \in S,\ k \in K_i \text{ and } b \in B \tag{5.34}$$

Constraints 5.35 determine the value of the binary variable indicating the existence of a production in a period. Here, M stands for a sufficiently large number. For every part i and its process p, we can have different tight M values such as the total production quantity for part i through process p in the month t, where $b \in B(t)$. Here, $B(t)$ is the set of periods in B which are in period t. If x_{ipb} has a positive quantity, then y_{ipb} is forced to be 1.

$$x_{ipb} \leq M\, y_{ipb} \quad \forall i \in F \cup S,\ p \in P_i \text{ and } b \in B \tag{5.35}$$

Constraints 5.36 and 5.37 are capacity related constraints. Constraints 5.36 calculate the total resource usage of resource r in period b. Here, a_{ipr} is the unit processing time of part i on resource r in process p. Constraints 5.37 set the upper bound for capacity usage.

$$\sum_{i\in I}\sum_{p\in P_i} a_{ipr}\, x_{ipb} = u_{rb} \quad \forall r \in R \text{ and } b \in B \tag{5.36}$$

$$u_{rb} \leq C_{rb} \quad \forall r \in R \text{ and } b \in B \tag{5.37}$$

The model contains a number of constraints related with planning issues mentioned in Section 4.3.3.1.

Issue 12 indicates that semi-finished and finished parts may have a minimum lot production constraint. Let μ_i be this minimum lot quantity. Following constraints handle Issue 12.

$$x_{ipb} \geq \mu_i\, y_{ipb} \quad \forall i \in F \cup S,\, p \in P_i \text{ and } b \in B \tag{5.38}$$

Issue 13 mentions that the CPM and scheduling model results should match in production quantities. Let X_{ipt} indicate the production requirement for part i via process p in month t, where T is the set of all months in the planning horizon. Productions of part i in month t must be equal to this quantity. We define $B(t)$ as the set of periods which are in month t. Constraints 5.39 ensure the consistency of capacity planning model and batch sizing model.

$$\sum_{b\in B(t)} x_{ipb} = X_{ipt} \quad \forall i \in F \cup S,\, \forall p \in P_i \text{ and } \forall t \in T \tag{5.39}$$

Constraints 5.40 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.

$$v_{grb} \geq \chi_{ig}\, y_{ipb} \quad \forall i \in F \cup S,\ \forall p \in P_i(r),\ \forall g \in G \text{ and } \forall b \in B \tag{5.40}$$

As Issue 14 indicates, production of some part families are performed only once in a month. That is, all production requirements of parts in those families should be satisfied when the production of the family once started during the month. Let G' be the set of families which are produced only once in a month. Production of families usually take longer than one period. In the MIP model, the production of a family in successive periods should be controlled. For this reason, we define new binary decision variables:

$$v^s_{grb} = \begin{cases} 1 & \text{if part family } g \text{ starts production on resource } r \text{ in period } b \\ 0 & \text{otherwise} \end{cases}$$

$$v^e_{grb} = \begin{cases} 1 & \text{if part family } g \text{ ends production on resource } r \text{ in period } b \\ 0 & \text{otherwise} \end{cases}$$

$$v^c_{grb} = \begin{cases} 1 & \text{if part family } g \text{ continues production on resource } r \text{ in period } b \\ 0 & \text{otherwise} \end{cases}$$

We have a set of constraints which define the relationship between the decision variables and ensure the continuity of family production in successive periods. Constraints 5.41 indicate that if a family has a production in a period b, it either starts, ends its production or it is in between.

$$v^s_{grb} + v^e_{grb} + v^c_{grb} = v_{grb} \quad \forall g \in G',\ r \in R \text{ and } b \in B \tag{5.41}$$

Constraints 5.42 and 5.43 indicate that there can only be one start and one end for the production of family g. Here, T is the set of monthly periods and $B(t)$ is the set of periods in month t.

$$\sum_{b \in B(t)} v^s_{grb} \leq 1 \quad \forall g \in G',\, r \in R \text{ and } t \in T \tag{5.42}$$

$$\sum_{b \in B(t)} v^e_{grt} \leq 1 \quad \forall g \in G',\, r \in R \text{ and } t \in T \tag{5.43}$$

Constraints 5.44 define the relationship between start and end of family production. That is, the starting period of family production must be earlier than the ending period.

$$\sum_{b \leq b^*} v^s_{grb} \geq v^e_{grb^*} \quad \forall g \in G',\, r \in R \text{ and } \forall b^* \in B \tag{5.44}$$

Constraints 5.45 provide the continuity of family production in successive periods. These constraints indicate the following: If a part family $g \in G'$ has production on resource r in a period before b and in a period after b, then this part family must be also produced in period b.

$$v_{grb^-} + v_{grb^+} = v_{grb} + 1 \quad \forall g \in G',\, r \in R \text{ and } \forall b, b^+, b^- \in B \text{ such that } b^- < b < b^+ \tag{5.45}$$

As indicated in Issue 15, some part families have minimum production duration constraints. Let those part families denoted by G''. Let τ_g be the minimum production duration defined for part family g. For any part family $g \in G''$, the following is true: $\tau_g < C_{rb}$ for any $b \in B$. Constraints 5.46 ensure that the production of a family in period b continues at least for τ_g seconds.

$$\sum_{i \in F} \sum_{p \in P_i(r)} \chi_{ig}\, a_{ipr}\, x_{ipb} \geq v_{grb}\, \tau_g \quad \forall g \in G'',\, r \in R \text{ and } \forall b \in B \tag{5.46}$$

Issue 16 considers the monthly part family sequences given by the planners. Let

G''' be the part families for which a production sequence is given on a resource r. Given the sequence of part families, e.g. $g_1 \rightarrow g_2 \rightarrow \ldots \rightarrow g_n$, where $g_1, g_2, \ldots, g_n \in G'''$, we calculate the time required to produce all parts in those families. Let $\nu_{g_j,t}$ be the time required for family g_j for month t. It is calculated as follows:

$$\nu_{g_j,t} = \sum_{i \in F} \sum_{p \in P_i(r)} \chi_{i,g_j}\, a_{ipr}\, X_{ipt}$$

where X_{ipt} is the monthly production requirement of part i. Given the part family sequence $g_1 \rightarrow g_2 \rightarrow \ldots \rightarrow g_n$ and $\nu_{g_j,t}$ for all g_j in the sequence, we determine the start and end periods of family productions. Let $b'_{g_j,t}$ and $b''_{g_j,t}$ be start and end periods for production of family g_j in month t, respectively. Constraints 5.47 ensure that the production of parts in family g_j can only be performed between periods $b'_{g_j,t}$ and $b''_{g_j,t}$.

$$x_{ipb^*} = 0 \quad \forall i \text{ such that } \chi_{i,g_j} = 1,\, p \in P_i(r),\, \forall g \in G''', \tag{5.47}$$

$$\forall b^* \text{ such that } b'_{g_j,t} > b^* \text{ or } b''_{g_j,t} < b^* \text{ and } \forall t \in T$$

Issue 17 mentions the production transition rules between semi-finished part families. Let G^s be the set of semi-finished part families. Production change rules between semi-finished parts, i.e. papers, are given as follows: For paper families g_i, g_j and g_k, we have the following constraint, $g_j \prec g_k \prec g_l$, which means that if a paper i_l in g_l will be produced after a paper i_j in family g_j, a paper i_k of family g_k must be produced in between. In MIP model, we want to ensure that parts for necessary production changes are assigned in the same period. We define Constraints 5.48 for every part families with similar rules.

$$v_{g_j rb} + v_{g_l rb} = v_{g_k rb} + 1 \quad \forall g_j, g_k, g_l \in G^s \text{ such that } g_j \prec g_k \prec g_l \text{ and } \forall b \in B \tag{5.48}$$

The objective of batch sizing model 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 cost of unsatisfied requirements. Cost parameters are determined by a similar normalization and prioritization scheme explained for CPM in Section 5.1.2.

Let c_{ip} be the unit production cost for part i and C be the total production cost and it is given by

$$C = \sum_{i \in I} \sum_{p \in P_i} \sum_{b \in B} c_{ip} \, x_{ipb}$$

Let h_i^q be unit inventory holding cost of part i for requirement type q, where $i \in F$. For semi-finished parts, we have h_{ik} as the unit inventory holding cost. Let H_F and H_S be the total inventory holding costs for finished and semi-finished parts, respectively.

$$H_F = \sum_{i \in F} \sum_{q \in Q} \sum_{b \in B} h_i^q \, I_{ib}^q$$

$$H_S = \sum_{i \in S} \sum_{k \in K_i} \sum_{b \in B} h_{ik} \, I_{ikb}$$

Let u_i^q be unit unsatisfied requirement cost of part i for requirement type q, where $i \in F$. Different requirement types have different priorities. That is, satisfying a requirement with high priority on time has much more importance than satisfying a requirement with low priority. Hence, for different requirement types, we have different unit costs, which increase with increasing priorities. Let U be the total unsatisfied requirement cost.

$$U = \sum_{i \in I} \sum_{q \in Q} \sum_{b \in B} u_i^q \, U_{ib}^q$$

Let f_{ikl} unit freight cost for part i from inventory location k to inventory location l, where $i \in S$ and $k, l \in K_i$. We define F as the total freight cost for semi-finished parts.

$$F = \sum_{i \in S} \sum_{k \in K_i} \sum_{l \in K_i \setminus \{k\}} \sum_{b \in B} f_{ikl}\, z_{iklb}$$

Let ru_r be the unit resource usage cost and RU be the cost of total resource usage.

$$RU = \sum_{r \in R} \sum_{b \in B} ru_r\, u_{rb}$$

The cost function of MIP model is given in 5.49.

$$Z_{BSM} = C + H_F + H_S + U + F + RU \tag{5.49}$$

Batch sizing model is an MIP model formulated as follows:

BSM: min Z_{BSM}

subject to 5.30, 5.31, 5.32, 5.33, 5.34, 5.35, 5.36, 5.37, 5.38, 5.39, 5.40, 5.41, 5.42, 5.43, 5.44, 5.45, 5.46, 5.47, 5.48
where

$$x_{ipb} \geq 0 \quad \forall i \in F \cup S,\ \forall p \in P_i \text{ and } \forall b \in B \tag{5.50}$$

$$I_{ib}^q,\ U_{ib}^q,\ x_{ib}^q \geq 0 \quad \forall i \in F,\ \forall q \in Q \text{ and } \forall b \in B \tag{5.51}$$

$$I_{i0}^q \geq 0 \quad \forall i \in F \text{ and } \forall q \in Q \tag{5.52}$$

$$I_{ikb} \geq 0 \quad \forall i \in S,\ \forall k \in K_i \text{ and } \forall b \in B \tag{5.53}$$

$$z_{iklb} \geq 0 \quad \forall i \in S, \forall k, l \in K_i \text{ and } \forall b \in B \tag{5.54}$$

$$DD_{ib} \geq 0 \quad \forall i \in S \text{ and } \forall b \in B \tag{5.55}$$

$$u_{rb} \geq 0 \quad \forall r \in R \text{ and } \forall b \in B \tag{5.56}$$

$$y_{ipb} \in \{0,1\} \quad \forall i \in F \cup S, \forall p \in P_i \text{ and } \forall b \in B \tag{5.57}$$

$$v_{grb} \in \{0,1\} \quad \forall g \in G, \forall r \in R \text{ and } \forall b \in B \tag{5.58}$$

$$v^s_{grb},\, v^c_{grb},\, v^e_{grb} \in \{0,1\} \quad \forall g \in G', \forall r \in R \text{ and } \forall b \in B \tag{5.59}$$

The number of decision variables in BSM can be calculated as follows:

- Production quantity variables (5.50): $|F \cup S| \times |P| \times |B|$
- Variables for ending inventory, unsatisfied demand and production quantity based on requirement types (5.51): $|F| \times |Q| \times |B|$
- Initial inventory variables (5.52): $|F| \times |Q|$
- Ending inventory variables (5.53): $|S| \times |K| \times |B|$
- Semi-finished part transshipment quantity variables (5.54): $|S| \times |K|^2 \times |B|$
- Dependent demand variables (5.55): $|S| \times |B|$
- Resource usage variables (5.56): $|R| \times |B|$
- Production assignment variables (5.57): $|F \cup S| \times |P| \times |B|$
- Production assignment variables for families (5.58): $|G| \times |R| \times |B|$
- Additional production assignment variables for families (5.59): $|G'| \times |R| \times |B|$

Total number of decision variables is given by $2 \times |F \cup S| \times |P| \times |B| + |F| \times |Q| \times (|B| + 1) + |S| \times |B| \times (|K|^2 + |K| + 1) + |R| \times |B| \times (|G| + |G'| + 1)$, where $|F \cup S| \times |P| \times |B| + |R| \times |B| \times (|G| + |G'|)$ of them are binary variables. The number of constraints can be calculated as follows:

- Inventory balance equations for finished parts (5.30): $|F| \times |Q| \times |B|$
- Initial inventory equations for finished parts (5.31): $|F|$
- Total production equations for finished parts (5.32): $|F| \times |B|$
- Dependent demand equations (5.33): $|S| \times |B|$
- Inventory balance equations for semi-finished parts (5.34): $|S| \times |K| \times |B|$
- Production assignment constraints (5.35):$|F \cup S| \times |P| \times |B|$
- Resource usage and capacity constraints (5.36 and 5.37): $2 \times |R| \times |B|$
- Minimum lot constraints (5.38): $|F \cup S| \times |P| \times |B|$
- Total production constraints (5.39): $|F \cup S| \times |P| \times |T|$
- Part family assignment constraints (5.40): $|F \cup S| \times |P| \times |G| \times |B|$
- Family constraints for finished parts which are produced only once in a month (5.41, 5.42, 5.43, 5.44 and 5.45): $3 \times |G'| \times |R| \times |B| + 2 \times |G'| \times |R| \times |T|$
- Family minimum production constraints (5.46): $|G''| \times |R| \times |B|$
- Family sequence constraints (5.47): $|F| \times |G'''| \times |R| \times |B|$
- Paper family constraints (5.48): $|G^s|^3 \times |B|$

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:

(i) Sequencing rules regarding product family restrictions
(ii) For finished goods, the level of importance of customer orders and the time of the earliest customer order
(iii) 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
(iv) 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. The scheduling algorithm is shown in Figure 5.1.

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

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

Create production batches given by x_{ipb}'s $\forall\, i \in F \cup S$, $\forall\, p \in P_i$ and $\forall\, b \in B$ from batch sizing model.
Schedule converting production batches. (Figure 5.2)
Schedule paper production batches. (Figure 5.3)
Reschedule converting production batches given paper availabilities. (Figure 5.4)

Figure 5.1. Scheduling Algorithm.

In the algorithm shown in Figure 5.2, 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 $B_{ip}^{[j]}$.

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.

Figure 5.2. Schedule converting batches.

In the algorithm shown in Figure 5.3, 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 $B_{ip}^{[j]}$.

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 $ST(B_{ip}^{[j]}) = \max_{j' \leq j}$ 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.

Figure 5.3. Schedule paper batches.

Due to paper schedule, the availabilities of papers can be calculated. In the algorithm shown in Figure 5.4, 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 Figure 5.2.

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

Figure 5.4. Reschedule converting batches.

6. IMPLEMENTATION

Mathematical models and sequencing algorithms are implemented on ICRON, a software especially developed for supply chain optimization purposes. ICRON is an object oriented modeling system and it provides a visual algorithm development environment. That is, the software provides a flexible development environment where almost any algorithm that can be implemented. ICRON is also capable of communicating with other system like ERP's or any other database systems. [42]

6.1. Integration of Models

Capacity planning, shift planning and scheduling models run in an integrated fashion where outputs of some provide inputs of others. Figure 6.1 summarizes input/output relations between models and order of runs.

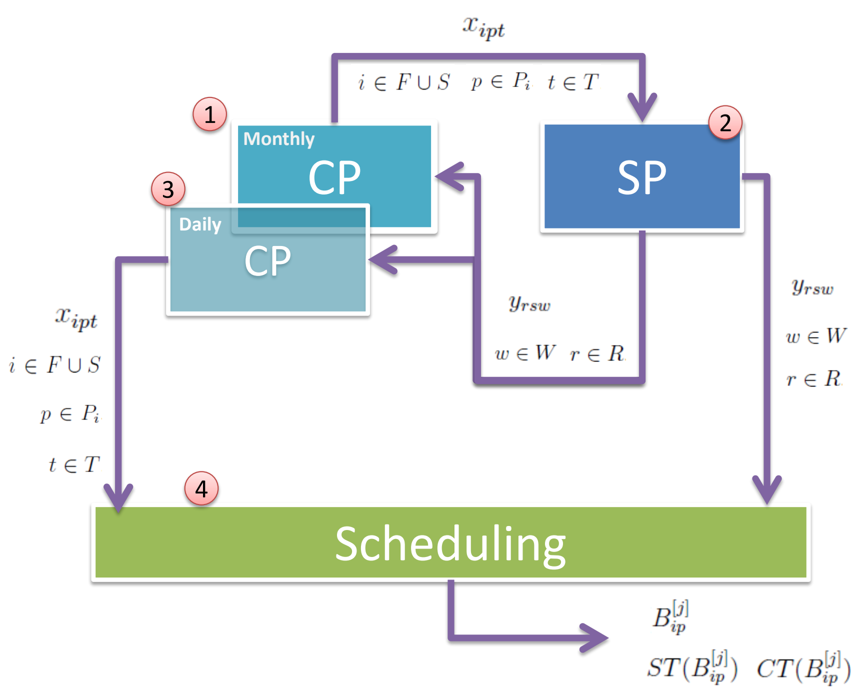


Figure 6.1. Integration of three models.

Capacity planning model (CPM) has two run modes; first mode is used in monthly runs and second mode used in daily runs. At the beginning of each month, sales department generates new forecasts for the next four months. Based on those new forecasts, CPM runs with "full" capacity, that is, resource capacities, RC_{rt} $\forall r \in R$ and $\forall t \in T$, are calculated such that they are going to operate 7x24 (see (1) in Figure 6.1). Resulting production quantities are fed to shift planning model (SPM) to determine weekly shift plan for the next four months. Almost every day during the month, small adjustments on forecasts occur. To reflect those changes on the production plan, CPM runs in second mode, where the installed capacities generated by SPM are considered as regular capacity for resources.

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 month is 30 hours, the smallest shift assignment for that month is obtained by assigning shift type 1 to one week and 0 to the remaining weeks. Total working hours in that month turn out to be 48, since there will be 6 working days and 8 working hours for each day. It is not possible that the resources are going to be shut down in the remaining 18 hours. For this reason, the shift plan generated by SPM is taken by the CPM as input 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. Every day many changes occur in forecasts, customer orders, acquisition plans etc. For this reason, CPM runs frequently. Second mode of CPM, which is used in frequent runs, usually daily, utilizes the shift plan generated by SPM in modeling the capacity constraints. That is, the active shift plan is used to calculate resource capacities, RC_{rt} $\forall r \in R$ and $\forall t \in T$. In this model the possibility to use more capacity than the SPM dictates is also taken into account. Deviation from installed capacity is allowed by the additional capacities, i.e. OC_{rt} $\forall r \in R$ and $\forall t \in T$. Remember that, using additional capacity has a higher cost than using regular capacity. If there is additional capacity used in the optimum solution, the planners are informed of the additional capacity requirements to run SPM and generate a new shift plan.

The SPM is executed at the beginning of each month for all resources (see (2) in Figure 6.1). Planners can re-run the SPM for all production resources or a subset of those as needed.

Fourth step shown in Figure 6.1 is the scheduling model, where the monthly production plan generated by the CPM and shift plan generated by the SPM are taken as inputs 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. As explained in Section 5.3, the first phase of the scheduling algorithm is solving the 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. The model runs after the run of daily CPM and at any time when significant changes occur in master data and in shop floor.

6.1.1. Manual Overrides

The models run regarding the information gathered from a number of different sources like ERP, planners' decisions and other data sources. There may be cases that the planners have more information than those sources which cannot be transferred into written data. Phone calls from various departments, a sudden breakdown in shop floor or planners' own experiences are examples for such information. To be able to project this information to the plan we developed some override mechanisms.

6.1.1.1. Capacity Planning. Towards the end of 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 4.3.1.1). In CPM, we set the decision variables for production quantity of first month to zero, i.e. we write Constraint 6.1 for every selected part i and its process $p \in P_i$. To prevent infeasibility due to minimum inventory level constraints (constraints 5.11 and 5.8), we remove those constraints related with the selected parts for the first period.

$$x_{ip1} = 0 \tag{6.1}$$

The planners may also decide on minimum production level of parts using a certain process. This may arise from the fact that the planners want to select a process, which has in fact less priority, to be able to control resource allocations. To handle this override, we insert new constraints to the model given the minimum production quantity. Constraint 6.2 is written for selected processes of selected parts, where ρ_{ipt} stands for minimum production quantity for part i and its process p in period t.

$$x_{ipt} \geq \rho_{ipt} \tag{6.2}$$

6.1.1.2. Shift Planning. As indicated in Section 4.3.2.1 Issue 11, planners may decide to fix shift plans for some weeks for various reasons. For fixed weeks, we create constraints shown in 5.26.

After SPM runs, generated shift plan is taken by th CPM as input. CPM runs in such a way that the capacity constraints (5.6 and 5.7) are modeled with respect to installed capacities. However, there may be cases where installed capacities do not meet the new production requirements or they turn out to be a lot more than actually needed. In such cases, planners are informed about the capacity requirement changes. They have two options to change the shift plan according new requirements: (1) re-run the SPM or (2) change the shift assignments manually. Remember that there are five shift types from 0 to 4, i.e. $S = \{0, 1, 2, 3, 4\}$. By increasing or decreasing the number of shifts assigned to a week, planners can adjust the installed capacities.

6.1.1.3. Scheduling. The manual override mechanisms in scheduling part increase the responsiveness of the system. In scheduling, planners take daily decisions. Sudden changes in the planning environment have direct effects on their decisions.

Planners have three manual override mechanisms on the resulting schedule:

- Changing the order of batches (Algorithms in Figures 6.2 and 6.3)
- Changing the size of batches (Algorithms in Figures 6.4 and 6.5)
- Changing the resource of batches (Algorithms in Figures 6.6 and 6.7)

After all override actions, batches are rescheduled where their start and completion times are recalculated. Rescheduling is needed due to possible changes of paper availability and changes in projected inventories of parts.

In the algorithm shown in Figure 6.2 shows the steps after a change in the order of batches on a converting machine. Here, we assume that the $B_{i^*p}^{[j]}$ is the batch whose start time is changed. Let ES_{i^*} be the time where $B_{i^*p}^{[j]}$ wanted to be scheduled and let r be the resource where this change occurs. ES_i is only positive for the selected batch, i.e. for $i = i^*$, and it has no value for other batches.

In the algorithm shown in Figure 6.3 runs for an order change on a paper production resource. Here again, we assume that the $B_{i^*p}^{[j]}$ is the batch whose start time is changed. ES_{i^*} indicates again the time where $B_{i^*p}^{[j]}$ wanted to be scheduled and we call r as the resource where this change occurs.

The algorithm in Figure 6.4 shows the steps after a change in the batch size of a finished part. Here, we assume that the $B_{i^*p}^{[j]}$ is the batch whose batch size is changed. Let BS_{i^*} be the new batch size for $B_{i^*p}^{[j]}$ and let r be the resource where this change occurs.

The algorithm in Figure 6.5 runs for a batch size change on a paper production resource. Here again, we assume that the BS_{i*} is the new batch size for batch $B_{i^*p}^{[j]}$ and we call r as the resource where this change occurs.

Unschedule all batches $B_{kp}^{[j]}$ on resource r such that $ST(B_{kp}^{[j]}) > \min\{ST(B_{i^*p}^{[j]}), ES_i^*\}$ and $k \in F$.

if No unscheduled batches **then**

STOP

else

Sort unscheduled batches 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.

$\pi(B_{ip}^{[j]})$.

end if

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 $ST(B_{ip}^{[j]}) = \max\{ES_i, \max\{ES_i', \max_{j' \leq j \text{ and } k \in F}\{CT(B_{kp}^{[j']})\} + s_{ik}\}\}$ 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

Figure 6.2. Change the order of batches on a converting machine.

Unschedule all batches $B_{kp}^{[j]}$ on resource r such that $ST(B_{kp}^{[j]}) > \min\{ST(B_{i^*p}^{[j]}), ES_i^*\}$ and $k \in F$.

Sort unscheduled batches with respect to following criteria:

Assigned period of $B_{ip}^{[j]}$, i.e. $[j]$.

Paper production change rules.

$\pi(B_{ip}^{[j]})$.

Set $ST(B_{ip}^{[j]}) = \max\{ES_i, \max_{j' \leq j \text{ and } k \in S}\{CT(B_{kp}^{[j']})\} + s_{ik}\}$ 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.

Reschedule converting machines due to new paper schedule (Figure 5.4).

Figure 6.3. Change the order of batches on a paper machine.

The algorithm in Figure 6.6 shows the steps after a change of assigned resource of a converting batch. Here, we assume that the $B_{i^*p}^{[j]}$ is the batch whose resource and start time are changed. Let ES_{i^*} be the time where $B_{i^*p}^{[j]}$ wanted to be scheduled. While changing the resource, user also changes the process of the batch. Let p^* be the process of the batch related with the new resource and p be the previous process. ES_i is only positive for the selected batch and it has no value for other batches.

The algorithm in Figure 6.7 runs for the change of assigned resource of a paper batch. Here again, we assume that the $B_{i^*p}^{[j]}$ is the batch whose start time and assigned resource are changed. ES_{i^*} indicates again the time where $B_{i^*p}^{[j]}$ wanted to be scheduled and we call p the previous process and p^* new process of the batch.

6.2. Integration of Planning System with Other Systems

The planning system implemented in ICRON has interactions with a number of other systems which is also shown in Figure 1.2. Master data containing information about all products, their production routings, bill of materials, acquisition plans etc.

Unschedule all batches $B_{kp}^{[j]}$ on resource r such that $ST(B_{kp}^{[j]}) > ST(B_{i^*p}^{[j]})$ and $k \in F$.

Determine the earliest time ES_{i^*} that the paper which is used by batch $B_{i^*p}^{[j]}$ is ready to use and determine new $ST(B_{i^*p}^{[j]})$ such that

$ST(B_{i^*p}^{[j]}) = \max\{ES_{i^*}, \max_{j' \leq j \text{ and } k \in F}\{CT(B_{kp}^{[j']})\} + s_{ik}\}$.

Recalculate the completion time of $B_{i^*p}^{[j]}$: $CT(B_{i^*p}^{[j]}) = ST(B_{i^*p}^{[j]}) + BS_{i^*}\, a_{ipr}$, where a_{ipr} is unit production duration on resource r through process p.

if No unscheduled batches **then**

  STOP

else

  Sort unscheduled batches with respect to previous scheduled start times.

end if

for All batches in sequence **do**

  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

Figure 6.4. Change the batch size on a converting machine.

Unschedule all batches $B_{kp}^{[j]}$ on resource r such that $ST(B_{kp}^{[j]}) > ST(B_{i^*p}^{[j]})$ and $k \in S$.

Recalculate the completion time of $B_{i^*p}^{[j]}$: $CT(B_{i^*p}^{[j]}) = ST(B_{i^-p}^{[j]}) + BS_{i^*}\, a_{ipr}$, where a_{ipr} is unit production duration on resource r through process p.

if No unscheduled batches **then**

STOP

else

Sort unscheduled batches with respect to previous scheduled start times.

end if

for All batches in sequence **do**

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.

Remove scheduled batch from sequence and go to Step 4.

end for

Reschedule converting machines due to new paper schedule (Figure 5.4).

Figure 6.5. Change the batch size on a paper machine.

Unschedule all batches $B_{kp}^{[j]}$ on resource $r(p)$ such that $ST(B_{kp}^{[j]}) > ST(B_{i^*p}^{[j]})$ and schedule them in the same sequence they had in previous schedule on $r(p)$.

Unschedule all batches $B_{kp}^{[j]}$ on resource $r(p^*)$ such that $ST(B_{kp}^{[j]}) > ES_{i^*}$.

Sort unscheduled batches on $r(p*)$ 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 par family in G.

$\pi(B_{ip}^{[j]})$.

if No unscheduled batches **then**

  STOP

else

  Sort unscheduled batches with respect to previous scheduled start times.

end if

for All batches in sequence **do**

  Determine the earliest time ES_i' that the paper which is used by batch $B_{ip}^{[j]}$ is ready to use.

  Set $ST(B_{ip}^{[j]}) = \max\{ES_i, \max\{ES_i', \max_{j' \leq j \text{ and } k \in F}\{CT(B_{kp}^{[j']})\} + s_{ik}\}\}$ 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

Figure 6.6. Change the assigned resource of a converting batch.

Unschedule all batches $B_{kp}^{[j]}$ on resource $r(p)$ such that $ST(B_{kp}^{[j]}) > ST(B_{i^*p}^{[j]})$ and schedule them in the same sequence they had in previous schedule on $r(p)$.

Unschedule all batches $B_{kp}^{[j]}$ on resource $r(p^*)$ such that $ST(B_{kp}^{[j]}) > ES_{i^*}$.

Sort unscheduled batches on $r(p^*)$ with respect to following criteria:

Assigned period of $B_{ip}^{[j]}$, i.e. $[j]$.

Paper production change rules.

$\pi(B_{ip}^{[j]})$.

if No unscheduled batches **then**

  STOP

else

  Sort unscheduled batches with respect to previous scheduled start times.

end if

for All batches in sequence **do**

  Set $ST(B_{ip}^{[j]}) = \max\{ES_i, \max_{j' \leq j \text{ and } k \in S}\{CT(B_{kp}^{[j']})\} + s_{ik}\}$ 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.

  Remove scheduled batch from sequence.

end for

Reschedule converting machines due to new paper schedule (Figure 5.4).

Figure 6.7. Change the assigned resource of a paper batch.

are retrieved from ERP system of the company. Sales department provides forecast data and gets information about possible sales opportunities from planning department. shop floor integration is maintained by a system called Production Management System (PMS) which has connections with ERP system and ICRON.

6.2.1. Integration with ERP System

ERP system maintains all data regarding the products and production environments. Models in ICRON are constructed based on the data retrieved from ERP system. That is, active products for which a production plan should be generated, definitions of processes by which a product can be produced, active resources etc. constitute the main information for the construction of models.

There are two main types of data received: (1) "static" data which do not change or changes of which occur very rare, (2) "dynamic" data which change frequently. The components of "static" data received from ERP system are listed below:

- Production plants, inventory locations and their definitions.
- Definitions of semi-finished, finished products and raw materials, e.g. code, description, unit of measure, type etc.
- Routing options of semi-finished and finished products, i.e. resource and bill of material combinations which can be used to produce them.
- Resources and their definitions.
- Unit production durations on resources of different routing options.
- Bill of materials, i.e. raw material requirements for unit productions based on routing options.

Data we call as "dynamic" mainly contain information which describe current situation of the whole production environment. The content of those data is listed below:

- Inventory levels of all products and materials in different inventory locations.

- Customer orders, deliveries and order returns.
- Acquisition plan of materials and products which can also be procured.
- Open production orders, i.e. production orders released to shop floor, their planned start and end times and remaining order quantities for the ones which have already started execution.

6.2.2. Shop Floor Integration

To be able to generate appropriate production plans, capturing the present situation of the shop floor is very important. For instance, when we consider CPM, initial inventory levels of products directly effect the production requirements for the whole planning horizon. For scheduling model, they have a direct influence on priority determination among various production batches. In this section, we introduce the means of shop floor integration and the data transferred through this integration.

The company has a shop floor monitoring system called Production Management System (PMS). The system composed of a software which is integrated with converting machines. The software takes open production orders assigned to every converting machine given the sequence of orders on the resource. The system automatically counts the produced items and feeds this information to ERP system online. With this information, PMS triggers ERP system to update the inventory levels of product and materials used in the production of that product.

After scheduling model runs, planners select some production batches to be released to shop floor. The release is realized in two steps. In first step, ICRON calls a function of ERP system to create a production order with the specifications of the selected production batch such as size, start and end times, scheduled resource, product code etc. ERP system generates a production order code for this new production batch and returns it as output of the called function. After that, ICRON sends the production order information to PMS where a sequence for this production order on the given resource is generated.

Capture of production order realizations is performed differently for paper production. An online system like PMS is not applicable for these resources. For this reason, every morning, the realizations of the previous day are collected and fed to ERP system by employees. Therefore the initial inventory levels for semi-finished products and for their materials in ERP system do not reflect the reality during the day. To have the right initial stock values, we developed algorithms in ICRON which project the inventory level information from the beginning of the day towards the current time when the models are going to run. That is, taking the difference between current time and beginning of the day, the theoretical production amounts for papers are calculated. Given the theoretical production quantities, the initial inventory levels of papers and of their materials are adjusted.

There are also other information regarding the shop floor which is not stored in ERP and not captured by PMS. This kind of information is handled using ICRON and saved to a local database. The following items are saved to local database via ICRON.

- Maintainance schedule of resources and holidays: The periodical maintenances of resources and holidays are important in calculation of available capacities. This information affects the decisions of all three models.
- Shift plan: For SPM, the shift plan for the first week is an important input, since it cannot be changed during the week and it directly affects the shift plan of the following weeks.

6.2.3. Integration with Sales Department

There is a two-way interaction between sales and planning departments. Sales department generates demand forecasts on a monthly basis and sends them to planning department. Both departments are continuously evaluating the sales and production environment such as market conditions, actions taken by competitors like introducing new products, and sales realizations. With all these considerations, forecasts may be updated jointly by the sales and the planning departments within the month.

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. After CPM is run and the paper production requirements for the finished products with given monthly forecasts, the remaining available capacity is calculated for each month. This remaining capacity can be allocated for export papers. Sales department is informed about the allocation of the excess capacity, so that they can manage possible external demand for tissue paper.

7. CONCLUSION

In this thesis, 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.

We composed the planning problem of the company into three phases: capacity planning, shift planning and scheduling. 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 aims to generate the appropriate shift plan, which consists of weekly shift assignments, given the production requirements and regulations originating from labor union. In scheduling phase, detailed production plan for the next two weeks is generated. That is, the size, start and completion times of production batches for finished and semi-finished products are given as a result of scheduling phase.

In capacity planning, the 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 runs separately for each resource. Scheduling problem is solved in two steps. In first step, a mixed integer programming (MIP) model, i.e. batch sizing model, runs which is very similar to capacity planning model. Here, the model has smaller time buckets and shorter planning horizon. After the production batches are determined in MIP model, they are scheduled using a heuristic procedure.

All three modules are implemented using the development environment provided by ICRON Supply Chain Optimization System [42]. The developed planning system operates integrated with other systems of the company such as ERP, Production Management System (PMS) etc. Data flows related with planning activities are realized among those systems via 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, improved inventory mix etc.

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 level that they could cover a demand of 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 can also see the bottlenecks in the capacity. So, they can manage productions such that they do not face any loss of sales. They can also guide the sales department by revising forecasts.

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 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. The main reason is that the planning system accelerated the daily operations of planners. For instance, planners had to spend a full day for the long term production planning at the beginning of each month and revisions on plan during the month took more than one hour every day. The operation durations are decreased to one hour for the beginning of each month and half an hour for revisions. 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. It also decreased the time spent for production order releases from 2 hours to 10-15 minutes.

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