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An Empirical Study on Scheduling in the Process Industries

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1 Introduction

Only in recent years software companies began to develop information systems for production planning and scheduling that are specific to the needs of the process industries. Similar systems and concepts for the discrete manufacturing industry had been discussed and implemented for a long time (cf. *Scheer 1990*).

In the process industries, e. g. the chemical and the pharmaceutical industry, food industry, paper industry, etc., either individual software solutions for special problems have been developed or standard software has been used which was originally made for the discrete manufacturing industry. Both solutions have their disadvantages: The individual solutions are usually not as powerful and as highly integrated as modern standard software. Standard software for the discrete manufacturing industry, on the other hand, does not meet the specific demands of the process industries, since there are many differences between these industries.

During the last years several approaches have been made to develop standard software especially for the process industries, for example special scheduling systems. One of these approaches is currently being developed in the European research project CAPISCE. This project, which is funded by the Commission of the European Communities under the ESPRIT-programme, aims towards creating an integrated information system that meets the demands of the process industries. The consortium consists of Zeneca, SAP, IDS, Digital and IWi. Since there are already powerful systems for the process control level as well as for the enterprise level (which is not so different from the discrete manufacturing industry), the project mainly focuses on the management of the plant level, including scheduling. The software that is being developed consists of the following modules: Scheduling, Resource Management, Inventory Management, Recipe Management, Batch Management, Management Report & Control, Link to Business Level, Link to LIMS (laboratory information system) and Link to Process Control. For an overview about the CAPISCE-project, see *Loos, Scheer 1994b* and *Loos 1993b*.

To ensure that the software actually is useful for the process industries, it is tested in two plants of Zeneca. However, it is not sure if all requirements of different types of production can be found within these two testbed plants. Especially scheduling is a critical point where many specific requirements can be found. Further research into these requirements for scheduling in the process industry was necessary to validate the concepts developed within CAPISCE.

There are only few publications discussing differences between the discrete manufacturing and the process industries. Special process industry-related requirements can be found in *Schürbüscher, Metzner, Lempp 1992*. How to apply the discrete industry's planning concepts to the process industries is explained in *Hofmann 1992*. Loos discusses characteristics of the process industries and outlines a concept for an integrated information system (cf. *Loos 1993a*). Jänicke describes a scheduling system which has been developed especially for the needs of these industries (cf. *Jänicke 1992*).

There is a huge number of publications about scheduling in the discrete manufacturing industries, but only few about similar topics in the process industries. Most papers in this area only deal with very specific scheduling-related optimisation problems and their mathematical solutions. Examples for such problems can be found in *Heuts, Seidel, Selen 1992*; *Ku, Karimi 1991*; *Smith-Daniels, Ritzmann 1988* and in *Musier, Evans 1989.* Even on a conference called "Computer Integrated Manufacturing in the Process Industries", held in 1994 in New Brunswick, N. J., most talks about scheduling addressed rather mathematical optimisation problems than how scheduling can be efficiently supported by an integrated information system (cf. *Smith, Randhawa 1994; Wang, Luh 1994*). Many of the problems discussed can only be applied to one case but not to the problems of other plants in the same industry. Usually it is also necessary to make simplifications for creating a mathematical model, so that it is difficult to apply the results to the real system.

An example for the discussion of a broader class of process industry-related scheduling problems is *Overfeld* 1990. An outline of production planning and scheduling in the process industries and how it can be supported by an information system can be found in *Loos, Scheer 1994a.*

To get a better picture about which specific requirements for scheduling can be actually found in the industrial practice, IWi has carried out an investigation among five companies of the process industries, the results of which are summarised in this paper.

2 Design of the Study

2.1 Objectives

The main objective of the study was to evaluate requirements for scheduling systems specific to the process industries, with special emphasis on batch production. To find out these requirements, a detailed investigation of selected plants had to be carried out, including the following topics:

- Production structures within the plant
- Interconnections with other plants
- Long term production planning on the enterprise level
- Scope and methods of scheduling in the plant
- Information systems supporting production and scheduling
- Special problems and requirements concerning production planning and scheduling

2.2 Scope

To define the scope of the study, the central terms of the title, which are 'scheduling' and 'process industries' have to be clarified. The definitions which are given are more practical oriented rather than theoretical according to the empirical character of the study.

In discrete industries parts are manufactured and assembled in lot sizes which vary from one to several thousands. In discrete industries there are usually synthetic bills of materials. This means that an end product consists of several components. By-products only occur in the form of waste, e.g. chips. The production steps are stable and the results can easily be determined in advance. Parameters like input quantities and production duration are depending linearly on the output quantity. There are mainly shaping processes rather than material transformation processes (*Riebel 1963*). Typical examples for discrete industries are the machine building industry, the automobile industry or the plant engineering industry.

Process industries deal with chemical or physical transformation processes of material which can be described by process engineering methods. Different branches like chemical and oil industry, food industry, paper industry and rubber industry belong to process industries. In process industries there are synthetic bills of materials (pharmaceutical industry) as well as analytic bills of materials (oil industry). Beside of waste, valuable by-products are common, especially with analytic bills of materials. Bills of materials can have cyclic dependencies (e.g. catalysts) or variable and substitutive quantity relations. Processes are generally subject to instability, so the production description may have to include non-linearities and validity ranges for process parameter values .

Depending on the material flow, processes can be distinguished into continuous and discontinuous production. Continuous production is characterised by a constant flow of material in specific configurations of equipment. Such processes are typical for the basic industry, e.g. petroleum refinement. In discontinuous production, on the other hand, a given quantity of a substance, called batch or lot, is produced (*SP88*). Container equipment like vessels and tanks is typical for discontinuous production. In order to be able to react flexibly to the needs of the market, a trend to discontinuous production - also called batch production - can be detected. Because continuous production usually is done in special equipment, each of which processes only a few products, and batch production is carried out on equipment for a wider range of products (*Riebel 1963, p. 104*), scheduling problems occur to a higher degree in batch production. Therefore the study focuses on process industries with batch production.

To reduce the complexity of production planning and control and to meet the requirements of the organisational structure of a company, hierarchical, multistage planning concepts (*Scheer 1994, Winter 1990*) are used. The organisational structure for process industries, which reflects the division of the business functions, are often presented as a five level pyramid (cf. figure 1, see also *Polke, Will 1990* and *Eckelmann, Geibig 1989*). All business functions, which need a high degree of communication and data transfer, are grouped in one level. To a certain extend the levels can act independently. However, each level has to communicate with its superior level and its subsequent level, and it has to stay within specified limits given from its superior level.

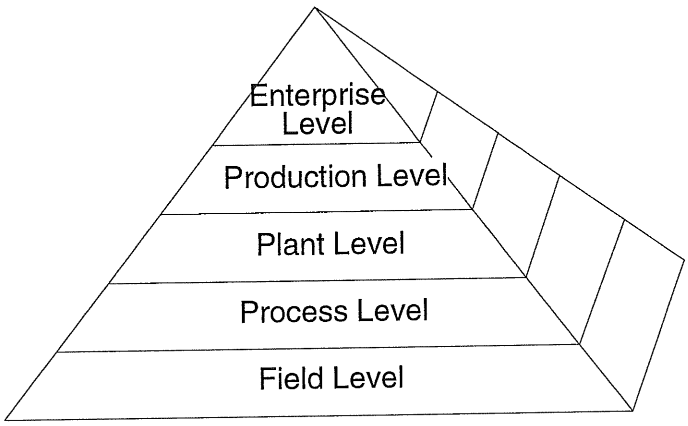


Figure 1: Multi-level Organisational Model for Process Industries (according to: *Eckelmann, Geibig 1989*

For a hierarchical, multistage planning concept in process industries, MRP II (Management Resource Planning) can be employed (*Hofmann 1992, Nelson 1983*). Typical planning stages following the MRP II concept are shown in figure 1 (*Loos 1993b*). The production planning level produces a master production plan and uses highly aggregated data. It can be carried out by the enterprise level. Material requirement and capacity requirement planning can be assigned to the production level. While these planning steps usually imply infinite scheduling, which means planning without capacity limits, the following steps often have to carry out finite scheduling. They can be done by the plant level. In the following, the term ‘planning’ is used for the more long term planning activities and the term ‘scheduling’ is used for the short the planning activities. The study concentrates on the scheduling aspects, but also takes into account the planning aspects since they are closely related to scheduling (cf. paragraph 2.4)

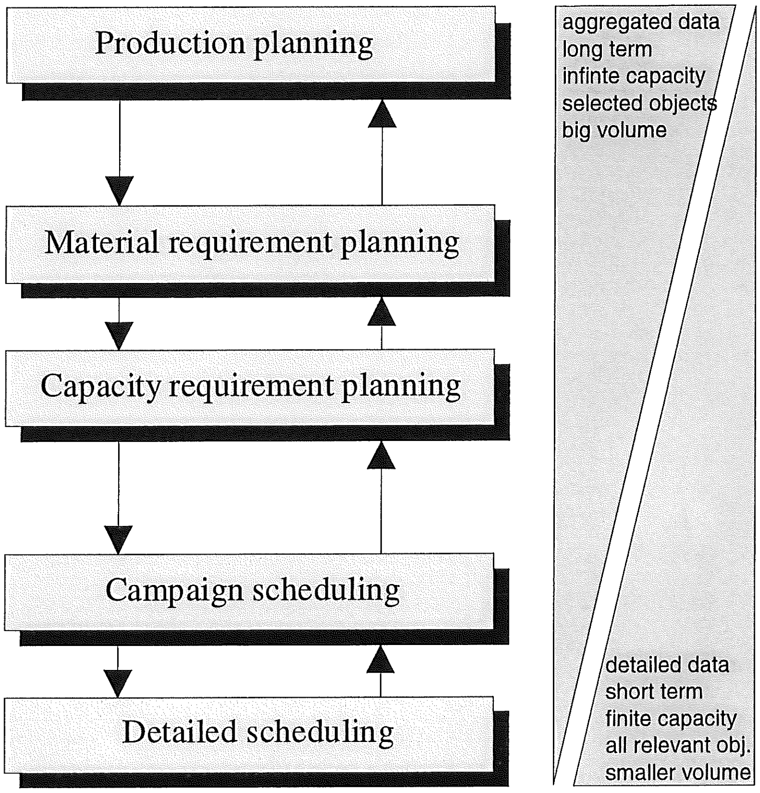


Figure 2: Planning and Scheduling Hierarchy (according to: *Loos 1993b*)

2.3 Selection of Plants

Typical examples of rather batch-oriented process industries can be found in the chemical industry, the pharmaceutical industry, and the food industry.

From these industries five companies have been selected for a closer investigation of the production structures, the production planning and scheduling methods as well as special problems and requirements for scheduling systems within one plant. The topics of interest were presented to production planning experts and information managers of each company, and they were asked to specify a plant within their company that they regard as typical for the structures and problems of their company.

The number of companies included in the study was deliberately kept small, since otherwise it would not have been possible to carry out thorough and detailed investigations in each plant.

The following companies and plants took part in the study:

- Company A.: Dye-production within a large German chemical enterprise
- Company B: Production of chemicals and pharmaceuticals in a large German chemical company
- Company C: Production of expandable polystyrenes and tensides in a large East-German producer of chemicals and synthetics
- Company D: Production of seeds in a French company
- Company E: Cigarette production in a German plant of an American company

With these five companies examples of several important process industries are included in the study. There may be very special industries within the process industries which are very different from those investigated, therefore it was not possible to address all possible requirements and problems of the process industries in this study. However, since the market shares and the economic importance of the selected companies (and other companies with similar products and production processes) are quite large and they produce a wide range of different products, a large part of process industry-related problems can be found within these companies.

With Company D, a seed producer, a rather untypical example has also been included in the survey, so that it could be investigated, whether such a company has problems that are totally different from those of a large chemical enterprise or if similar structures can be found in both industries.

In each plant it was possible to speak with the plant manager or another person responsible for the scheduling within the whole plant. In some cases interviews were also carried out with people of enterprise-wide production planning and with central information systems people. Since these people have a better overview over many plants they could judge which problems of the specific plant are also relevant to other plants. They were also interviewed about the co-ordination between different plants and between plant and business level, as well as about the company's IT-systems and strategies.

2.4 Questionnaire

To ensure the effectiveness of the interviews, a questionnaire had been worked out. The questionnaire helped to structure the interviews and to make sure that no important topic was omitted. It also helped to make the results of each interview more comparable.

The questionnaire was used as a guideline for the interviews, the questions on it did not allow simple answers, but they rather addressed topics and fields for discussion. An important criterion for designing the questionnaire was that it did not limit the possible answers to what the questionnaire's authors may have expected, but to allow the interview partners to speak about all aspects they regarded as important.

One example: In the questionnaire it was not presupposed that the company has exactly two planning levels called "business level" and "plant level", like this is typical for several planning concepts, but it was asked which planning levels there are in the company, and what is the task and the scope of each of these level. Thus it was possible to find out that the planning systems of some of the companies do not exactly match with such a two-level planning sys-

- General information about the company and the plant
- Production structures in the plant
  - Products
  - Processes
  - Equipment
  - Automation
  - Interconnections to other plants
- Structure and levels of production planning in the company
  - Scope of each level
  - Co-ordination between levels
  - Supporting Information systems
  - Strategies and methods
  - Interface between plant and higher planning level
  - Data held and used on each level
- Scheduling
  - Scope and responsibility
  - Level of detail
  - Time horizon
  - Objectives and criteria
  - Scheduling systems
  - Strategies, methods and algorithms
  - Data for scheduling
  - Resources that are scheduled
  - Delays and breakdowns
  - Evaluation of schedule
  - Feedback from process level
- Special requirements of the process industries

  A list of requirements was given, and each topic was discussed - if it can be found in the plant and how important it is, or how difficult a problem it is for scheduling, e.g.:
  - Campaign scheduling
  - By-products
  - Scheduling of cleaning procedures
  - Shared resources
  - ....
- Special problems and scheduling requirements in the plant
- Detailed description of one or two typical production processes in the plant
- Detailed description of the scheduling process

Figure 3: Structure of the questionnaire.

tem. In the following questions of the questionnaire it had to be assumed that there was at least some kind of "long-term planning" as opposed to the scheduling, but since the planning structure already had been discussed, it was possible to relate the questions to the company's actual planning levels in the discussion.

For the basic structure of the questionnaire see figure 3.

2.5 Evaluation of Interviews

The interview results were protocolled in a very detailed way. For all interviews there were at least two interviewers to ensure that no relevant aspect was forgotten.

Each protocol was then analysed separately, i. e. without comparing it to the other protocols, and the main topics and the most important requirements were extracted from each protocol as company-related results of the investigation.

Where possible, the results were presented to the interview partners and discussed so that details of the protocols could be corrected and the results could be validated.

In a second step, the protocols of all five interviews were compared, and differences and similarities concerning products, processes, production structures, planning levels, scheduling strategies, specific problems, etc. were evaluated.

Finally, the results, i. e. the most important requirements, were clustered and common problems were identified, as well as those problems that could be found only once but which are also remarkable, because they address basic problems that may be relevant in other companies as well, or problems which are very unexpected and thus not being addressed by common scheduling strategies and systems.

3 Production Structures in Selected Companies

This chapter gives an overview of the production structures and scheduling requirements of the five companies that have been investigated. For each company the following information is given:

- A short description of the company and its products
- A description of the production structures in the selected plant
- How production planning and scheduling is done at the moment
- Special problems and requirements concerning scheduling

3.1 Company A - Dye Production

3.1.1 Description of the Plant

Company A is a large German chemical company. The plant that has been investigated is part of the company's textile dye-division. The plants' main products are textile dyes and pigments. It also produces some other materials like intermediates. The plant is carrying out batch production, its main resources are reaction tanks and distillation units. The number of people working in the plant is about 80.

3.1.2 Production Structures

The total number of products of the plant is about 75, from which 20 to 40 are produced within one month. There are frequent changes of products. The plant's resources consist of 32 reaction tanks, several distillation units, additional equipment and a unit for purification of exhaust gases.

The plant acts mainly as supplier for other plants within the division, but there are also products that are produced from start to finish within the plant. With two thirds of all products the plant typically carries out one production step. A product may need up to seven production steps, therefore it may processed in altogether five to seven different plants (usually all within the same division). The processing time of a batch within the plant is between half a day and two weeks, the average is about two days. Before and after processing, the products are usually stored in a central warehouse outside the plant.

There are many strong interconnections with other plants and suppliers. This includes the exchange of products and services, such as purification of exhaust gases and effluent treatment.

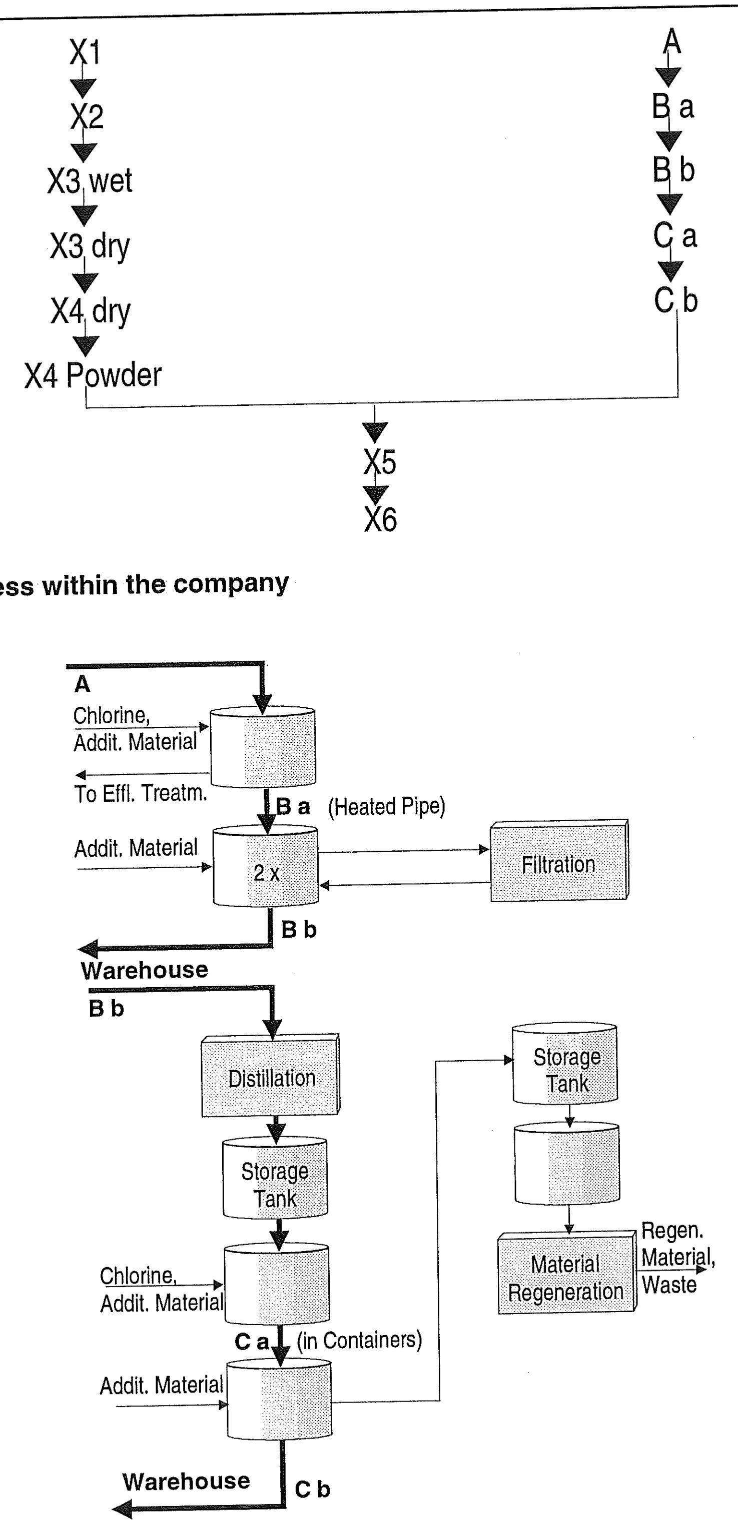
For a certain production the required equipment is usually being assembled together to a unit that is fixed for the whole production time and that is used exclusively for one product at the same time. Typically there is one major piece of equipment, i. e. a reaction tank, and other devices are mounted to that tank as required.

There are also some products with two or more reaction steps within the plant. For some of them there is a fixed train, consisting for example mainly of two connected vessels, which are never dismounted and which are only used for one specific product. Other such trains are mounted together only occasionally when there is a product requiring that train. The equipment of such a train is used otherwise during the rest of the time.

Mounting and dismounting units and trains is done by the division's service team, such changes take typically about two days. The costs for this service are very high.

The production is partly automated, there are some process control systems.

The supply of raw material and intermediate products is organised centrally by the division.



a) Entire process within the company

b) Process within the plant (right branch of a))

Figure 4: A sample production process (dye-production).

A sample production process can be seen in figure 4. In this diagram the real material names have been replaced, they are not relevant for understanding the scheduling-related facts of the production. Upper case letters denote products, while lower case letters stand for a certain state, such as "dry", "Powder", etc. Figure 4a shows an overview about the most important steps for producing a certain dye. These steps are carried out in several plants. The steps in the right upper branch are carried out in the investigated plant. Figure 4b contains the details of these steps.

The first two tanks are connected by a pipe that can be heated, they are therefore used together every time when this production is done. During the rest of the time the tanks can be used for other productions, and then they are usually not used together. The process in the second tank has to be repeated once. Between these two process, the material is being filtered.

After the first two tanks, the resulting intermediate product - B b - is stored in the warehouse, because the capacities of the first two tanks are different from those of the following tanks, and it is not possible to directly continue processing the same number and size of batches as they come from the second tank.

How the process of figure 4 is being scheduled, will be described in paragraph 3.1.3.2.

3.1.3 Production Planning and Scheduling

There are two main levels of production planning and scheduling:

- Central planning on division level,
- Scheduling on plant level.

3.1.3.1 Central Planning

Central planning on division level uses long-term prognoses and actual customer orders to determine - in accordance with the marketing department - the demands for each product. These demands are compared to the warehouse stock. If this stock is going below a certain level, production orders are given. A production order contains the product, the amount and the due date. The demands for intermediate products are calculated from the demands for finished products. Central planning has therefore a bill of materials for each product, as well as the capacities of each plant. However, these capacities are theoretical maximum capacities, which are available when the required resources are not used for any other production. The people from central planning usually also have experience about what can and what cannot be produced, e. g. they may know that two certain products cannot be produced in a certain plant at the same time, since they both need a special bottleneck resource.

For each product there are quantities known that can be produced economically according to the resource capacities. The quantities of the production orders, resulting in campaigns at plant level, therefore are always equal to that economical number or a multiple of it.

The exact planning of due dates is done in co-operation with the plants. Since it is not easy to co-ordinate all the plants, there is a considerable stock of intermediate materials, but it is intended to reduce these stocks, since the divisions costs for material on stock are very high.

Central planning is supported by a MRP II-System which is an individual solution for the company.

3.1.3.2 Scheduling

Scheduling is carried out on plant level. For each production order from central planning, the required resources have to be determined. In many cases there are several alternative resources for each product. The start date for the production order is then set to the first time at which all these required resources are together available. According to the resource capacities, size and number of batches and their processing time are determined. All these batches form a campaign, i. e. these batches are intended to be produced sequentially on the same equipment without interruption.

In the case that is shown in figure 4, always the same resources are used, so that the capacities and the batch sizes are always the same, and the number of batches and the processing time can be calculated at the beginning, and no decisions about alternative resources have to be made.

For resources that are permanently assembled in the same way, only the sequence of campaigns has to be determined. There are even a few one-product units which are rather easy to schedule.

For all other resources which can be combined and connected in many different ways, the reaction tanks as most expensive resources are scheduled first (primary resources). There are recipes defining which tank can be used for which product, but the scheduling people know this by heart. They know also which resources usually are bottlenecks in each kind of production. After scheduling the primary resources, the availability of additional resources is checked. If not all necessary resources are available, the campaign has to be rescheduled. Scheduling requires a lot of experience, e. g. about fixed or possible connections of tanks or about which unit can be used for which product.

For legal reasons it is expected that the flexibility of assigning campaigns to resources will decrease, since for many productions it will be necessary to get a permission for each assignment that is used. This tendency decreases the complexity of scheduling.

The time horizon for scheduling is between one and two months, the smallest time intervals are days.

Since the plant is usually very busy and the due dates of production orders are not always realistic (cf. paragraph 3.1.3.1), the due dates of many orders cannot be met by the schedule.

The earliest possible start date is reported back to central planning. Central planning can either agree to the dates given from the plant or it can decide that the current schedule has to be changed, e. g. when this particular production is very important. Such a change can be one of the following measures:

- Interruption of a current production.
  This is very time- and cost-intensive since it requires additional set-ups and cleanings

- ❍ Changing another scheduled production to other equipment
- ❍ Changing dates of other productions

The scheduled dates for each production order have to be confirmed by central planning. There is a meeting every month for discussing the schedule, but usually there have to be daily changes of the schedule, and the plant and central planning have to co-ordinate these changes, usually by telephone.

The main objective for scheduling is meeting due dates. Other criteria, such as maximum utilisation of resources, especially of the expensive reactors, are also paid attention to. However, the plant's performance is measured by the total quantity produced. It is tried to keep the number of product changes small, since they require a lot of time and money. Production orders from central planning can have priorities assigned, indicating whether they may be delayed or if they are very urgent.

Scheduling is supported with a manual gantt-chart. The work force is not scheduled explicitly. Is is regarded as a weak point that labour utilization is difficult to determine, which is necessary at least on work force qualification level. Quality controls are not scheduled, but in some cases they affect the schedule when production cannot continue until the test results have been determined.

The pipes which are available at the plant as well as the local distribution of the resources are restrictions for scheduling, since not all units can be connected to each other, and tanks which are very far apart from each other should not be used for processing the same material, because the material has to be moved between these two tanks. Further restrictions result from central resources, such as effluent treatment facilities. These resources have limited capacities and they have to be shared between different productions, in special cases even between different plants.

The production is also quality dependent. If the quality standards are not met, there are rules what to do with the material, and more material of sufficient quality has to be produced.

For new products the production process has to be tested in the plant. Such test productions require time and equipment and they are difficult to schedule since they are not well known.

3.1.4 Special Problems and Requirements

The main facts and problems concerning scheduling that have been found in the selected plant of company A can be summarised as follows:

- ❍ There is a frequent change of products, the number of different products is high.
- ❍ Jobs compete for resources and services.
- ❍ There are central resources and services with limited capacities that have to be shared.
- ❍ Unit configurations can be different for each product.
- ❍ Changes of unit configurations are expensive and time consuming.
- ❍ Some unit connections are fixed, others can be changed, but not all connections are possible.

- The number of restrictions is quite high.
- Scheduling is done manually, it strongly depends on experience.
- The schedule has to be changed frequently.
- The production is quality-dependent.
- There are many strong interconnections with other plants.
- For long-term planning only theoretical, maximum capacities of the plants and some rules of experience are known.
- There is a high co-ordination effort between the plant and central planning.
- There is no integrated information system for supporting production planning and scheduling.
- The service team for set-up and clean-out is working only one shift per day while the plant is operating 24 hours per day.

3.2 Company B - Chemical and Pharmaceutical Production

3.2.1 Description of the Company

Company B is a large German manufacturer of chemicals, pharmaceuticals, photographic products, etc. At this company it was possible to interview experts for production planning, scheduling and information systems within the entire company, rather than managers from one specific plant. Therefore it was possible to get an overview about important problems and requirements as they exist in different divisions and plants within the whole company.

3.2.2 Production Planning and Scheduling

3.2.2.1 Production Planning

Several production planning strategies can be found within the different divisions of the company. According to production planning strategies, the company's divisions can be grouped into three categories:

1. Pharmaceuticals, Dyes, Photography
2. Agrochemicals
3. Other Chemical Divisions

The divisions within each group have rather similar production strategies which can be characterised as follows:

1. Pharmaceuticals, Dyes, Photography

The numbers of different products are very high. Pharmaceuticals, for example, have about 10.000 different material numbers. 2.000 of these materials are input materials, i. e. they are purchased from outside the company. Typical bills of materials include about seven to eight components.

Production planning is done in regular intervals (i.e. once a month) with a time horizon of one year. From estimations of future sales, the required amount of each product is derived. According to the bills of materials the net amounts for production are then calculated. The actual plant capacities are regarded only on a very rough level. Some plants are known as typical bottlenecks. To make a more feasible production plan, these plants are looked at on a more detailed level. The sequence of plants that have to be passed by a certain product, are usually assigned infinite capacities for planning, and only theoretical processing times are considered. For the bottleneck plants, the calculation of the plan is interrupted, and they are planned under consideration of their capacities. However, how this is to be done, relies on human expertise, and the ways of doing this are not well documented.

In the pharmaceutical division, for example, a product has to pass twelve different plants on average, i. e. there are very high dependencies between different plants caused by the material flow. Typical total processing times are about nine months.

Between six and eight weeks before a production is planned to commence, the production requirements are given to the plants for scheduling. About two weeks before production starts, detailed finite scheduling is done. Usually it is necessary to discuss the details of the actual schedule between the central logistics department and the plant. Many manual changes of the production plan have to be made. The co-ordination between the plants is done by the central logistics department.

2. Agrochemicals
In this division, only the calculation of required net amounts is done centrally. The real production planning, including plants and times, is rather made by negotiating between the plants and central planning. The different plants are co-ordinated by the central logistics department.

3. Other Chemical Divisions
In the other divisions, there is no central logistics department. Once a year, a five-year sales plan is made, which is then used for calculating required net quantities and rough plant utilisations. For each group of products, the co-ordination is done by direct communication between the plants. There is an information system for handling external as well as internal orders, i. e. orders from customers or orders from other plants. For some products, the sales department communicates directly with the scheduling people in the plants.

For the future it is planned to create groups of plants which will be able to plan in an independent way. At the moment there is no IT-solution for passing the long-term production plans into the plants. There is a batch run once a month. Changes between these batch runs are not given to the plants.

In the future it is intended to use more information about the plants' actual capacities for production planning to increase the planning quality. Among other things, this would ease deciding about using alternative plants when the capacity of one plant has been exceeded. It is planned to define groups of products and groups of resources. These could be assigned to each other in a matrix. Then it would be easy to find alternative resources.

3.2.2.2 Scheduling

Scheduling is done on plant level. The plant receives a production requirement which includes the name of the product, the amount, the earliest and the latest time. Scheduling then determines the detailed assignment of production jobs to the plant's resources. This is usually done manually (manual gantt charts) or with individual software (spread sheet programmes, individual solutions, etc.). There is no integrated system for this task. In some plants scheduling systems (Leitstand) and their integration into the company wide information system are currently tested.

Recipes are stored decentrally in the plant, there is a work plan for each combination of product, plant and process. For each product one work plan is selected for production planning.. Special problems occur when there are alternative resources with different control equipment. When an alternative resource is used, a different control recipe has to be created. This requires flexible assignments of recipe to production jobs.

For the production of pharmaceuticals there is a very low flexibility, because according to FDA-requirements, for each product all equipment and processes must be validated in advance. For this reason it is usually not possible to use alternative resources. The scheduling complexity is therefore rather low.

Scheduling strategies rely on human experience and heuristic methods. In some areas it was tried to implement operations research-methods, but no general concepts that could be used for several different plants, were developed. Usually it is even the problem to get all relevant information which is needed for using optimisation algorithms.

Most plant managers do not have enough information about the consequences of their decisions for other plants. Direct communications between plants does not lead to a good overall solution. Usually the plant managers use time buffers and sometimes material buffers to avoid problems.

Further requirements towards scheduling systems include the management of fixed processing durations as well as durations that depend on the amount of material and durations that depend on the type of equipment that is used. Another important requirement is the availability of co-ordination mechanisms between different operations. For long-running productions it should be possible to supply not all material at the beginning, but during production as required (overlapping material supply).

3.2.3 Special Problems and Requirements

The main facts and problems concerning scheduling that have been found in the plants of company B can be summarised as follows:

- There are many interconnections between plants within a production chain.
- The number of different products is very high.
- With pharmaceuticals there is a very low flexibility, according to FDA-requirements.
- There is no integrated information system that includes the plants.
- There is much co-ordination required between scheduling and central planning.
- The plant capacities are only roughly known within long-term production planning, or not considered at all.
- Scheduling is mostly done manually.
- Experience and heuristic scheduling strategies are very important.
- The main problem for scheduling is to get all necessary information for creating a schedule.
- The plant manager does not know the effects of his decisions on other plants.
- The durations of operations may depend on the units being used.
- The durations of operations may depend on the amount of material.
- For long-running productions it should be possible to supply not all material at the beginning, but during production as required (overlapping material supply).
- There should be a flexible assignment of recipes to enable the use of alternative resources with different control equipment.
- There should be a co-ordination mechanism between different operations.

3.3 Company C - Expandable Polystyrenes and Tensides

3.3.1 Description of the Plant

Company C is a large East German chemical company. It contains three divisions: synthetics, organic chemicals and PVC. Since the German re-unification it has been tried to improve its competitiveness on the world market. This restructuring process is still not finished. Currently, the company builds several new productionplants, while it closes others with old technology and old production methods.

Interview partners at company C were managers from two different plants: one for tensides, the other for expandable polystyrenes (EPS), as well as from the central information systems department.

3.3.2 Production Structures

3.3.2.1 Expandable Polystyrene (EPS)

The interview based on the structures of the plant that is currently used. It will be replaced by a new plant in 1995. The resulting changes in the production structures were also discussed. At the moment about 50 people work in the plant.

The product is made in this plant entirely from start to finish. There is only one basic product, EPS, which has several variants. There are two basic types: normal and non-inflammable EPS, each of which has six or seven variants, which differ in sizes and types of coating.

The plant has its own laboratory with a staff of about ten people.

There are eight polymerisation reactors. Raw materials are styrol and some additional substances for stabilising the process and giving the product the desired properties. Handling the process is not easy, it is especially difficult to keep the required temperatures. Different reactors must not be in the same process stages at the same time since there is not enough cooling water. This is ensured by fixed production cycles. The reactors have to be cleaned after each batch.

The resulting grain sizes are distributed according to a Gaussian curve, but only certain grain sizes are desired by the customers. The other grain sizes are by-products.

There are two units for further processing the grains. About two-thirds of all batches are being covered with a fireproof coating. On the processing units alternating campaigns of normal and non-inflammable products are processed. The grains are grouped according to their size into seven fractions. After that, additional coating is done. In the new plant, this coating will be done related to the customer orders.

Before the non-inflammable products can be sold, the results of a seven days inflaming tests have to be awaited.

Batch tracking is complicated, because of several mixing processes during the production.

For the new plant an information system for the plant management is planned. A major requirement is the integration to the laboratory information system (LIMS). Another important requirement is that the plant can be operated manually in case the information system does not work.

3.3.2.2 Tensides

The second investigated plant produces tensides which can be used for washing powders. There are about 50 people working in the plant including the plant's laboratory.

The tenside plant is to some extent a supplier for other plants of the company, but it mainly makes products from start to finish. There are not many interdependencies with other plants, only some concerning energy and raw material supply. The raw material requirements of different plants have to be co-ordinated, since the size of the shared raw material tanks is rather small, and the actual demands for raw materials are known only a short time in advance. The pipeline which is used for some raw materials also has to be shared with other plants.

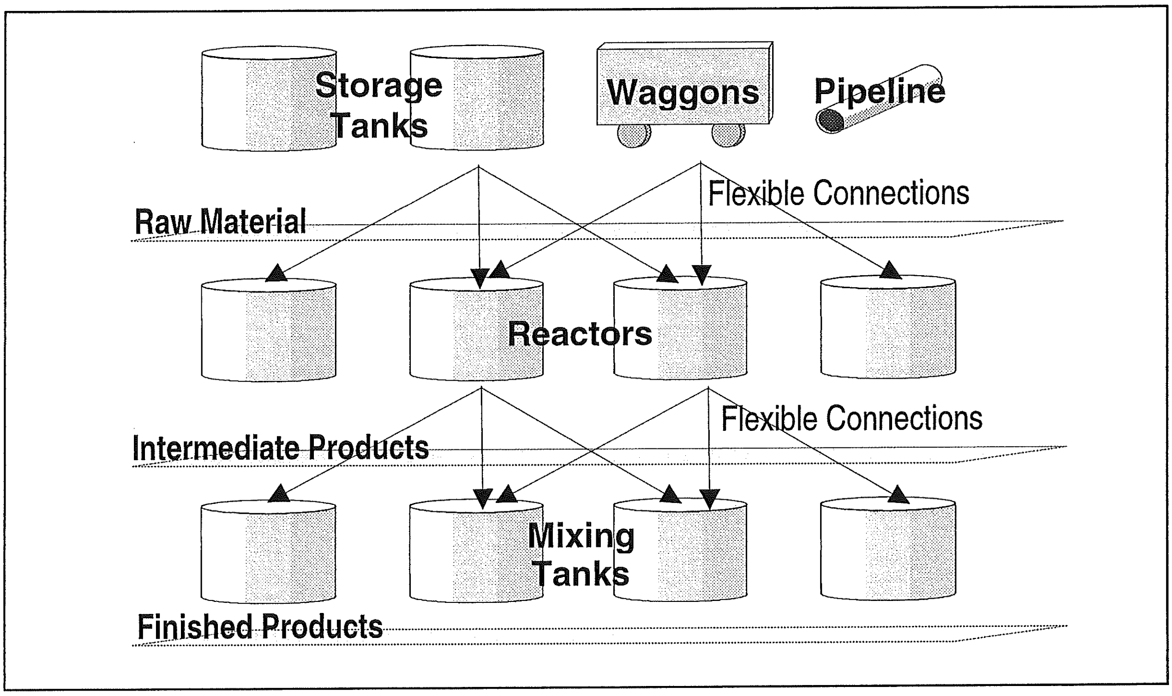


Figure 5: Production of tensides.

The basic production structure can be seen in figure 5. Raw materials are delivered via pipeline, in barrels or in wagons. They can be stored or immediately be used for production. The same tanks, however, can also be used for storing finished products.

The actual batch production takes place in one of 14 reaction tanks. One batch needs between 15 and 30 hours of processing time. For technological reasons there is a minimum size for batches. Not every product can be made in every reactor, because many products need specific equipment which can only be found at certain reactors. Sometimes reactors can also be used as storage tanks.

The semi-finished products of the tanks are then mixed in mixing tanks and filled into railway wagons. Batches are split for mixing, i. e. material from the same batch can go into different batches of different finished products. The filling stations are bottlenecks restricting the possibilities for loading and unloading wagons. Wagons can also be used as storages.

There are no fixed pipelines that connect different units, but flexible material distributing devices, which also are bottlenecks. Not every pipeline of such a distributing device can be used for every product.

There is a laboratory in the plant, i. e. the plant can carry out its own analyses. The times for such tests are determined by the production schedule. In some cases production has to be interrupted until the test results are available.

In the future the units will be controlled by a process control system.

Treatment of effluents and exhaust gases can sometimes be a problem. There are central units for these tasks in the company. These units have restricted capacities. There is a fixed portion of these capacities assigned to each plant.

3.3.3 Production Planning and Scheduling

3.3.3.1 Production Planning

There are three main levels of planning in the company: the business level, the division level and the plant level.

On the business level a yearly plan is made, including rough quantities for sales and for production. Based on this plan, each division makes its own yearly plan which takes into account bills of materials and theoretical plant capacities. The division's planning bases on sales forecasts, the yearly plan is split into segments of three months. There are monthly co-ordination meetings of marketing, sales and controlling departments and the plants. There are weekly co-ordinations between sales and production according to customer demands.

The plant is responsible for creating a schedule, i. e. the assignment of production orders to resources and sequencing.

3.3.3.2 Scheduling in the EPS Plant

Scheduling is currently done manually. This is sufficient for the present situation which is characterised by a rather simple production structure. In the new plant the situation will be a little more complicated, at least at the last production step, because of the customer specific coating.

Scheduling objectives are the reduction of the amount of material in the plant and a good utilisation of the resources. Scheduling also has to deal with by-products and how they can be used.

The production is dependent on the results of quality checks, i. e. parameters have to be changed according to actual grain size distributions, but this does not provide any scheduling problems.

3.3.3.3 Scheduling in the Tensides Plant

Each batch is related to a certain customer order. Quantities and dates are determined by the customer orders. There are no real by-products, but for technological reasons the real quantities are always larger than required and it is tried to sell these additional product quantities. In some cases, campaigns are created and scheduled.

According to customer orders, control recipes are generated, containing quantities, due dates and resources. These control recipes are then scheduled.

The main objectives for scheduling are:

- Creation of feasible schedules
- Reducing costs
- Reducing lead times
- Increasing resource utilisation
- Reduction of cleaning times and costs

Which kinds of cleanings are required for a certain change of products can be determined with some calculation rules and the use of a quality matrix.

A special problem for scheduling is caused by the high number and frequency of changes that have to be made to the schedule.

Currently scheduling is done manually, in the future a scheduling system will be used which will be integrated to systems for materials management and batch tracking. It will be connected to the business system and the process control system. Scheduling will then be done on-line. The system will check for dates and restrictions, as well as for the availability of resources and material. The most important requirements for a scheduling system were:

- Taking storages and pipelines into account for scheduling.
- Consideration of all relevant requirements and restrictions.
- Creation of feasible plans.
- Simulation (What-if-analysis).
- Cost calculations for production orders.
- Batch tracking.

3.3.4 Special Problems and Requirements

The requirements of EPS and tenside production are different, but in this paragraph remarkable problems and requirements from both plants are listed:

- Handling of by-products
- Resources have to be shared with other plants.
- Technological restrictions (e. g. minimum batch sizes).
- There is a high flexibility of assigning batches to reactors, but there are also many restrictions concerning the reactors' equipment.
- The restrictions are not documented in a structured way, but they are known by experience.
- Batches can be split, and the intermediate products are used in several final products.
- Filling stations and flexible connections between tanks and reactors are bottlenecks.
- There are restricted capacities for effluent treatment.
- Reduction of cleaning times and costs is important.
- The schedule has to be changed very often.
- Quality checks and laboratory tests should be regarded for scheduling, as well as waiting times for test results.
- Integration to the laboratory information system (LIMS) is required.
- Batch tracking is very important, also with several mixing processes.
- It should be possible to make simulations (what-if-analysis).
- All relevant restrictions must be in the system.
- The system must create feasible schedules.

3.4 Company D - Seed Production

3.4.1 Description of the Plant

Company D is a large European company, mainly concerned with the production of chemicals, pharmaceuticals, etc. There are three plants which are mainly concerned with seed production. The plant that has been investigated is based in South France, it mainly produces seeds for sugar beets and for sunflowers. In this survey only sugar beet seed production has been investigated, since for sunflowers the process is similar, but some production steps are omitted.

3.4.2 Production Structures

The plant receives the seeds from the growers, processes them and sells them mainly to sugar companies which distribute them to their farmers. The growing of the seeds, as well as the growing of the basic seeds (which are used for growing the commercial seeds) is also be planned in the company.

There are about 100 different products produced in the plant. The products can differ in respect to the genetic feature, the mixture ratios of different genetic combinations and the different coatings.

The equipment used in the plant is running mainly automatically, but it is being controlled mostly manually. Between the different process steps, the containers are being handled with forklift-trucks.

The most important steps of the typical production process of sugar beet seeds within the plant can be seen in figure 6. After the reception of the seeds from the growers, the seeds are stored between one and two days. The delivery time is planned in advance in respect to harvesting times and market needs. The farmers can store the seeds so that they need not to deliver it directly after harvesting but according to the planned times. The seed is being analysed, mainly to determine the humidity and the percentage of full seeds, i.e. seeds that can actually be used to grow plants.

The seeds are then being cleaned and separated according to size and gravity. The size of the seeds that can be used is between 3.5 and 6.0 mm. There is about 30% waste, i.e. seeds that are too big or too small, or empty seeds. This waste is being collected in a tank (any capacity problems that could occur can be solved by using additional containers, etc.), and it can be sold as animal feed. For cleaning and separating there are several lines that can be connected differently. After this process step, the seeds are being stored again, up to several months. There is also another quality control, the results of which are only known after up to ten weeks for some tests. It would be useful to wait for these results before continuing the production, but this is not always done. Negative test results may require not to use any seeds of the batch, or if the results are not that bad it may be possible to use the larger seeds and only to remove the smaller ones.

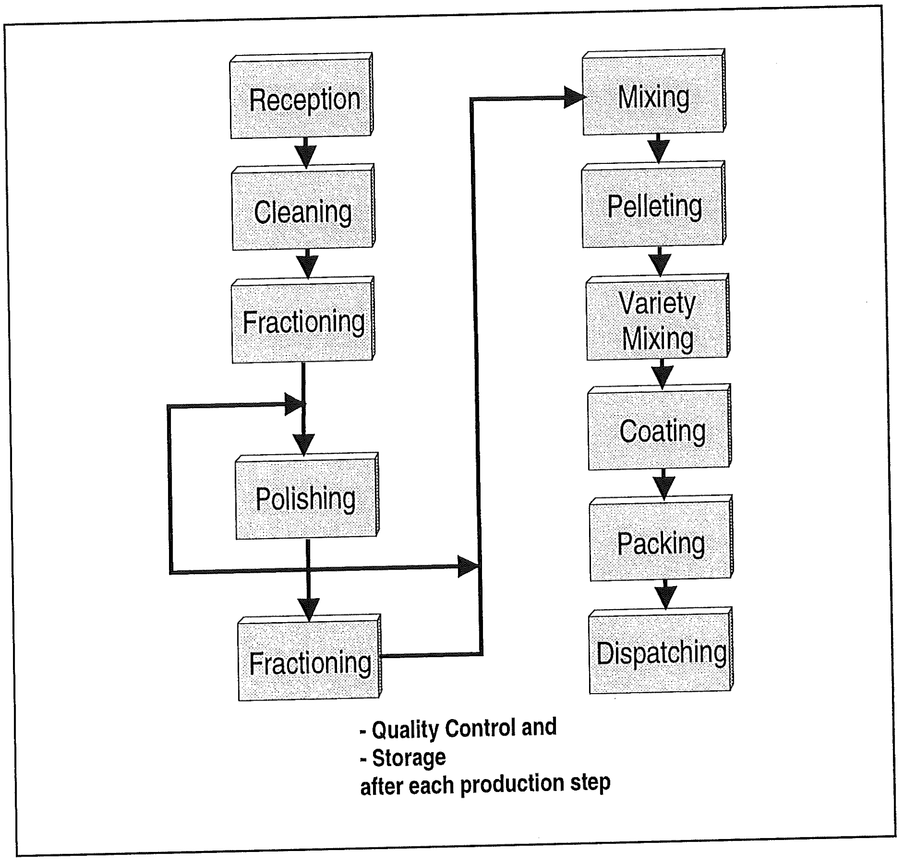


Figure 6: Sugar Beet Seed Production.

After each production step, the batch is being weighed. It is possible to store the seeds after each step. Usually it is necessary to carry out a quality control, and a significant amount of waste has to be removed (up to 10%)

In the next step, the seeds are being separated in two fractions according to their size. The machinery that is being used for this is the same as for the preceding step. The two fractions consist of the smaller seeds (3.5 - 4.5 mm) and the larger seeds (4.5 - 6.0 mm), each of which consists of about 45% of the batch (10% are waste). The seeds are then being polished. It is tried to reduce the size of the larger seeds by reducing the thickness of their shell through polishing. The larger seeds can be polished up to three times according to their remaining sizes. This cannot be determined entirely in advance.

The process of polishing and fractioning is called "processing". Due to necessary rework the processing time is not known in advance.

Seeds of different sizes are being mixed to produce a batch with a certain distribution of grain sizes. The batches produced by mixing are larger than the preceding ones.

Mixing of seeds within one genetic combination can be carried out at any stage of the production process, not only directly after processing. Seeds of different combinations can also be mixed to produce a certain variety of seeds. This can be done after processing, after pelleting and after coating. It is tried to wait as long as possible until mixing to receive greater flexibility for creating varieties according to the market demands.

Cleaning, fractioning and processing are mainly carried out in certain seasons (according to the harvest season), the following steps (pelleting and coating) are being done all year round.

The processed seeds can be sent to other pelleting stations of the company or they can be sold to customers who carry out the further steps themselves. During pelleting, the seeds are being covered with a mixture of pelleting material, fungicide, glue and water. Seeds that are too large after pelleting are removed, while seeds that are too small are being pelleted again. The variety mixing is typically done after pelleting. The last step is coating with insecticide, plastic and colour. The seeds are then being packed into bags and boxes which are being put on pallets. Finally they are being dispatched. Because of the expensive ingredients, the pelleting and coating yield in a high added value.

According to contracts with the customers, the company also accepts returns of seeds. The returns also have to be managed. In some cases they may be reused or mixed with other seeds.

3.4.3 Production Planning and Scheduling

3.4.3.1 Production Planning

Production planning mainly consists of making the "crop plan", i.e. it has to be determined how many hectares of each genetic combination should be produced and where this is done. The crop planning is being done centrally for all sites of the company.

The planning is based mainly on sales forecasts, since the crop plan has to be made more than one year in advance. According to the current stock and the current production, the amounts needed of each product are calculated, from which the number of hectares for each genetic combination can be derived.

The growing of basic seeds which are used to produce the commercial seeds has to be done two years in advance. There are more basic seeds being produced than actually needed, therefore there is usually enough flexibility for crop planning.

The capacities of the growers' fields and the capacities of the plants are restricting the maximum production, but this is usually not a problem. There also some other restrictions, e.g. of genetic combinations that must not be grown on fields that are situated too close to each other, etc.

The crop planning is mainly done manually, supported by a spreadsheet program. The knowledge about capacities and restrictions is mainly expert knowledge, it is not implemented in a system.

The main problem with crop planning is not to create a plan according to all restrictions and objectives, but to produce good sales forecasts.

3.4.3.2 Scheduling

Scheduling mainly consists of determining when the growers have to deliver their seeds, and when which batch is being processed on which equipment. Input to scheduling are mainly the actual customer orders and the expected amount of harvested seeds (according to their genetic combination and the quality). The latter is known from the crop plan and from quality controls on the fields. Since during the first processing steps the actual orders are not known yet, the planning for these steps is done mainly according to forecasts and experience, as well as to priorities given from the company level.

The last steps (especially coating) are usually driven by actual customer orders. To meet the customers' demands, it is necessary to produce the required mixtures in advance. On the other hand the flexibility for short-term changes is greater, when the mixing is done as late as possible.

The production schedule has to be adjusted to seasonal requirements, which result from the harvesting time for seeds as well as from the planting time of the customers.

The schedule is being changed several times a week. Since there is a large number of batches (about 700) with different processing states, which can be mixed in different variations, and the equipment can be used for different production steps, there is a great complexity for scheduling.

Further problems with scheduling are processing times and necessary reworks that are not known in advance, as well as other quality-dependent processing steps. Seeds that are being returned from the customer can sometimes be reused or mixed with other seeds. This also influences the schedule.

Between the processing of two batches on one machine it is sometimes necessary to clean the machine, but only when the genetic combinations of the two batches must not be mixed.

The laboratory for quality controls can be a bottleneck for the production that has to be taken into account for scheduling. In some cases it is necessary to send samples to laboratories of other sites, when a certain test cannot be carried out within the plant's laboratory.

The main objects to be scheduled are machines and material. Material is of special importance, since the main costs result from raw material. For other materials besides the seeds, such as treating materials, there are long-term contracts with the suppliers, so that it is always possible to get the required amount of these materials. Personnel is not being scheduled.

The main scheduling objectives are to satisfy orders at the right time and to produce the right amount of each combination and each variety, so that there is not too much material of each kind, that cannot be sold.

Scheduling is done manually on the basis of experience and expert knowledge. There are no special systems to support scheduling. However, scheduling is not seen as a very important problem at the moment, the production managers are more or less satisfied with the results of the manual scheduling.

The only problem mentioned was that there is only little transparency on what will be going on in the plant, i.e. the current version of the schedule is not well documented for everybody involved. The quality of the scheduling process is also very dependent from a single person's expert knowledge.

3.4.4 Special Problems and Requirements

The main facts and problems concerning scheduling that have been found in the selected plant of company D can be summarised as follows:

- The information systems of the different plants and of the business level are not sufficiently integrated.
- The current system is not always up-to-date, i. e. it does not always show the actual situation in the plant.
- The results of quality controls determine the following production steps.
- There are production steps the duration of which is not known in advance, due to rework.
- The production is very much dependent on the season.
- The first steps are customer independent while the last steps are done according to customer orders. To meet the demands, it is necessary to produce the required mixtures in advance, but the flexibility is greater when the mixing is done as late as possible.
- The laboratory can sometimes be a bottleneck.
- Scheduling is done manually, it relies heavily on expert knowledge.
- Batch tracking and documentation is a very important problem.

3.5 Company E - Cigarette Production

3.5.1 Description of the Plant

Company E is an international food and tobacco company. The plant that has been investigated is concerned with the production of tobacco and cigarettes. There are three cigarette plants of the company in Germany. The investigated plant makes cigarettes in batches, while other plants also carry out continuous cigarette production.

3.5.2 Production Structures

The plant carries out the entire process of cigarette production from the raw tobacco to the finished cigarettes. The number of different products is about 250. There are no interdependencies with other plants during the production, only the purchase of the raw materials and the distribution of the products is done for several plants.

Tobacco is produced in batches. For tobacco treatment there are only some possible quantities for a batch (e. g. 3t, 6t, ...). The lot sizes for cigarette production can be different, they are not restricted to certain sizes. The product has to go through six to seven production steps in the plant. After tobacco production, the production is split into several production lines. The number of possible paths is very high, because there are many possibilities of combining different units and additional equipment.

There are many dependencies between the different production processes. The different types of tobacco treatment have to be synchronised, there must be a co-ordination between tobacco treatment and cigarette production. Different jobs are competing for the same resources or the same equipment.

The plant is almost fully automated, only some silos and storages are handled manually. The connections between tobacco silos and the cigarette production lines are created by manually changing flexible pipelines.

The main steps of cigarette production can be seen in figure 7.

3.5.3 Production Planning and Scheduling

3.5.3.1 Production Planning

There are three main levels of production planning and scheduling:

1. European headquarters
2. Affiliate level
3. Plant level

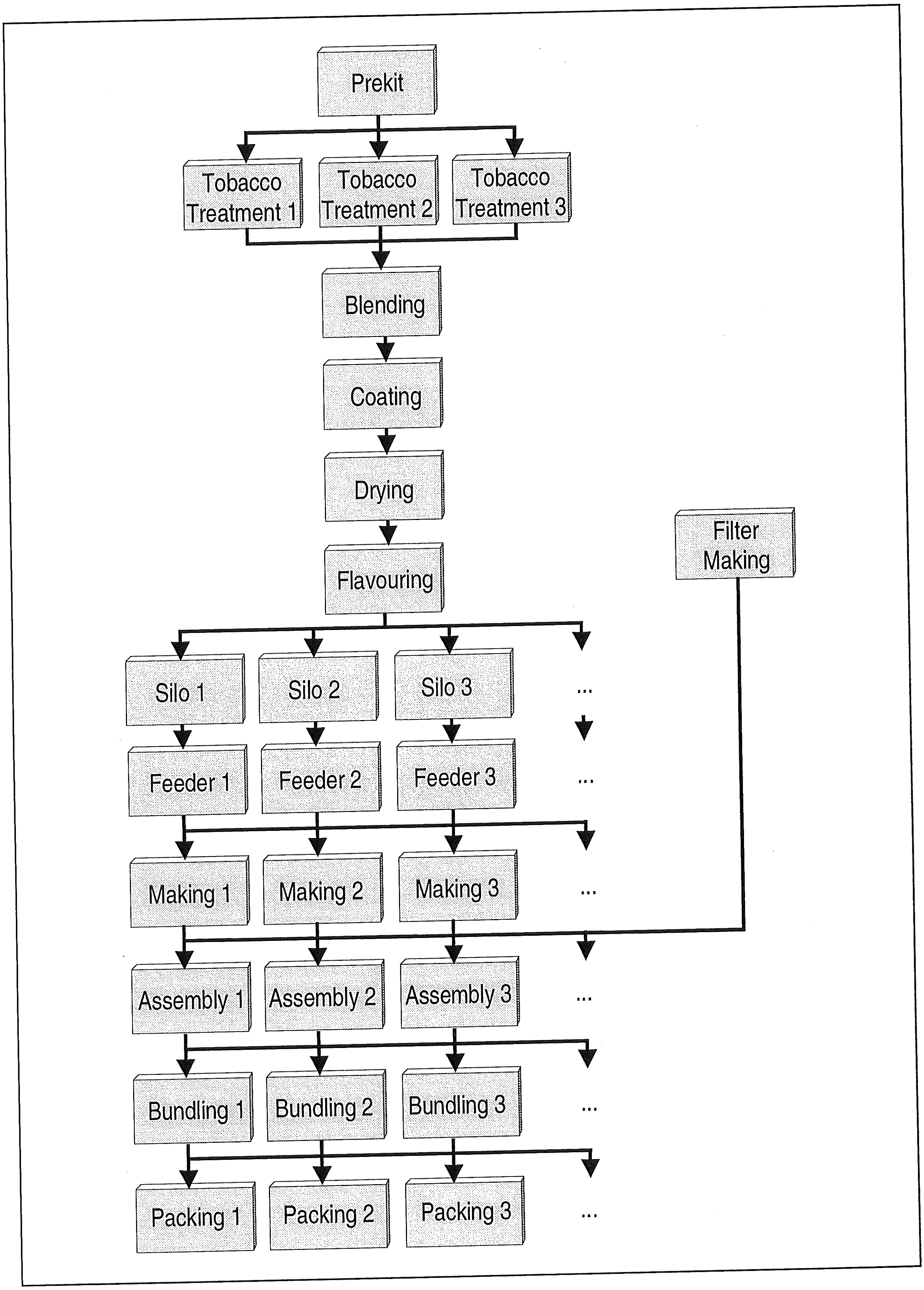


Figure 7: Basic material flow of cigarette production.

The European headquarters makes basic long-term decisions about which product groups should be manufactured.

The affiliate level is responsible for midterm planning of one or two countries. This includes quantities and due dates for each single product in each plant. The time horizon for the midterm planning is 12 months. Every month a new plan is made which differs from the preceding plan to a degree of about 20%. Further changes of about 20% are made during the current month. The raw tobacco purchase, which is also done on affiliate level, is planned with a time horizon longer than a year. There is an information system for production planning (individual solutions) which does the planning based on the resource capacities in each plant.

The plant schedules the jobs backwards from the final products, i.e. it assigns the jobs to the resources. For that it has to calculate the net quantity of each intermediate product from the bill of materials. Some intermediate products are made without relation to a certain order, they are produced on stock, according to their actual use and the quantities that are currently stored.

The co-ordination of these levels is done by personal communication, the different plants are co-ordinated via the affiliate level.

Production planning on affiliate level is very complicated. The number of single products that are planned only for the investigated plant is over 250, the planning horizon is 12 months. It has not been possible to make groups of products and of resources in a way that they do not overlap, because there are too many possibilities of assigning a product to a unit. At the same time there are many difficult restrictions. At the moment, overlapping groups are used, i.e. some of the products belong to more than one product group, and some resources belong to more than one resource group. This leads to incorrect production plans, e. g. a capacity may be scheduled for two different jobs at the same time. To avoid such errors, resources belonging to more than one group have to be planned separately, and the overall production plan is corrected.

3.5.3.2 Scheduling

The time horizon for scheduling is four weeks. The schedule is subject to frequent changes. Starting with the final products (about 250), all production steps are scheduled backwards. It is tried to create a schedule containing only a small number of product changes on each unit and to reduce the number of changeovers that are difficult and take a long time. Scheduling is based mainly on experience.

First the standard products with large quantities are scheduled, non-standard products with smaller quantities are added to the schedule later. After the schedule has been created, its feasibility is checked. If there are any conflicts, i. e. at the bottleneck resources, the schedule is changed accordingly (backtracking). The most common reason for changing the schedule is that not all required materials are available. They have to be provided before the set-up of a unit is started.

The most important scheduling objectives are:

1. Meeting due dates.
2. Reduction of costs (mainly for labour and for material on stock).

For each changeover the labour costs can be calculated and assigned to the product. Additional costs, i. e. for a night shift, are also assigned to the products.

Scheduling is done manually, the schedule is documented with a spread sheet program. In the future it is planned to use a scheduling system. The most important requirements for such a system are:

- Dynamic assignments of products to resources.
- Calculation of changeover times
- Consideration of different states of resources
- Different scheduling strategies: priority rules and user-defined strategies.
- Generation of different possible schedules and their evaluation.
- Possibility for manual scheduling.
- Graphical user interface (Gantt-Chart).

There are two special problems concerning scheduling:

1. The number of different changeovers is very high. It is therefore not possible to maintain changeover matrices for all units and all products. Currently the changeover times are determined roughly by several "rules of thumb". These rules will be implemented in the new scheduling system. Because the variety of products that are produced in the plant changes very often and new products are introduced, it is not possible to store only the changeovers that actually can take place with the current set of products, but there must be the possibility to provide for all theoretically possible kinds of changeovers which can be described with about 10 independent parameters of each machine and 10 independent parameters for each product.

2. Changeover times on a unit are not only determined by the two products that are processed before and after the changeover, but in some cases also from another product processed earlier on the unit. An example for this: For product one, a certain device had to be mounted to the unit. After that, product two has been produced for which the device was not needed, but since the device was not needed elsewhere it stayed on the unit. If a third product, which is produced after product two, needs the same device, this device need not be mounted anymore, because it is already there. The changeover time is therefore shorter than it would have been without the earlier production of product one. For calculating changeover times it is thus necessary to take different states of resources into account.

3.5.4 Special Problems and Requirements

The main facts and problems concerning scheduling that have been found in the selected plant of company E can be summarised as follows:

- There are many product changes, among them a significant number of entirely new products.
- The number of possible paths for a product is very high.

- There are shared resources, i. e. resources that can be used by more than one job at the same time.
- Overlapping jobs: A job can already start, when its predecessor has not been finished yet.
- There are many dependencies between different production processes.
- There is a large number of complicated restrictions which are not entirely documented.
- Co-ordination between midterm planning and scheduling is done only by personal communication.
- Scheduling is done manually, it relies heavily on human experience.
- One of the main problems are changeover and set-up costs.
- The actual changeover times are hard to determine because of the high number of possible product changes, they are only roughly calculated by "rules of thumb".
- Changeover times may also depend on the status of a machine.
- It has not been possible to aggregate resources and products for production planning so that the groups do not overlap and the correct quantities result for planning on the aggregate level.

4 Requirements for Scheduling Systems

In this chapter the most important aspects concerning scheduling that have been found in the selected companies are summarised, especially those aspects that have been found in more than one company or even in all companies. This study concentrates on scheduling rather than long-term production planning. However, many scheduling-related questions and problems can not be understood when nothing is known about the kind of long-term production planning that is used in the company. For many scheduling problems it is not possible to find solutions only on the plant level, but with an integrated view of the long-term planning with the embedded scheduling process. Therefore some of the topics discussed here include also long-term planning problems.

The main facts that have been described in detail in chapter 3 are summarised and the interview results of each company are compared. After discussing production structures and scheduling-related problems that have been found in the selected companies, requirements for scheduling systems in the process industry are derived.

This chapter does not give a complete overview of scheduling requirements in the process industry, since there may be more requirements in other than the selected companies. However, the topics in this chapter were considered as very important by most interview partners, both plant managers with a detailed insight into their specific plant, and information managers with a broad overview over planning problems in many plants. Therefore these topics are likely to be of importance also to other companies.

An overview over several topics that are related to scheduling or that cause special scheduling problems is given in table 1. For each of the five companies it is indicated whether a specific problem influences scheduling. For company C, in which two plants have been investigated, there are separate columns for each plant. For company B almost all items in table 1 are marked. This is because of the fact that the interview within company B was not related to one specific plant, but to scheduling problems throughout the entire company, and within a large company almost each of these problems can be found somewhere, but usually not all within one plant. The information given in table 1 must therefore be seen not so much as a means for a direct comparison of different plants, but rather for summarising which scheduling-related topics have been found in which company or plant.

From the fact that a topic is not marked for a given plant, it cannot be concluded that the corresponding statement is not true for that plant, but only that the interview partners did not regard it as a problem affecting scheduling (If a statement does not apply for a plant, it is also not marked, of course).

Production Structure: Complexity/Changes	Company A Dyes	B Chem.	C EPS	C Tens.	D Seeds	E Cig.
Low flexibility (singe-purpose equipm., legal regulations)		X	X			
High flexibility in resource assignment (multi-purpose equipment)	X	X		X		X
Large number of products	X	X				X
Large numbers of different paths	X	X				X
Many interdependencies between plants	X	X				
Frequent product changes	X	X				X
Frequent changes of schedule necessary	X	X				X
Frequent introduction of entirely new products	X	X				X
Special Scheduling Problems and Requirements						
Campaign scheduling	X	X		X		
Changeover times and costs are important	X					X
Use of alternative units	X	X		X	X	X
Durations depend on units that are used		X				
Durations depend on material quantities		X				
Changes of unit configurations	X	X		X		X
Changeable unit connections	X	X	X	X		X
By-products		X	X		X	
Quality-dependent production	X	X	X		X	
Quality tests have to be scheduled	X	X				
Production has to wait for test results	X	X		X		
Unstable products						X
Shared resources in the plant	X	X	X	X		
Shared central resources	X	X	X	X		
Overlapping production						X
Consideration of unit status						X
Uncertainties levelled out with buffers	X	X		X	X	X
Current Scheduling Situation						
Lack of transparency	X	X		X	X	X
Non-structured restrictions	X	X		X		X
High dependency on expert knowledge	X	X	X	X	X	X
Integration of Production Planning and Scheduling						
Lack of integration of scheduling into company-wide information system	X	X	X	X	X	
Co-ordination of production planning and scheduling difficult	X	X				X
Incorrect capacities used for production planning	X	X	X	X		X
Direct co-ordinations between plants		X				

Table 1: Scheduling situation in selected plants.

4.1 Complexity of Production Structures

The complexity of the production structures is an important factor that determines how difficult the scheduling task is. During the study it has turned out that in respect to scheduling complexity the range varies from simple to very complex.

Very simple production structures and a **low flexibility** can be found in some cases in the chemical industry, e. g. when a plant produces only one product on single-purpose equipment, and when the plant produces the entire product from start to finish. In such cases there are not many degrees of freedom for assigning jobs to resources, and there are not many interdependencies with other plants. Scheduling is therefore relatively easy, since only the sequence in which the orders should be produced has to be determined, and possibly a few decisions concerning product variations have to be made. An example for such a low flexibility can be found in the EPS-plant of company C.

Another case for low flexibility is given in companies of the pharmaceutical industry. Manufacturers of pharmaceuticals all over the world have to obey not only their national laws but also the very strict regulations of the American Food and Drug Administration (FDA). Under these regulations every piece of equipment that is used for a certain product has to be certified. This means that it is not possible to change between alternative resources. This also reduces the complexity of scheduling. This problem has been found in the pharmaceutical part of company B.

The other extreme that has been found in several cases is a very complex production structure. Complexity related to scheduling means that there is a large number of different jobs and resources, and that there are many degrees of freedom of assigning of jobs to resources. On the other hand there are usually also many interdependencies between different jobs, as well as different kinds of restrictions and strong interdependencies with the plant's environment, and that changes occur frequently.

Scheduling in such a case is a very difficult task, because the numbers of variables and conditions are very large and the situation changes frequently. Usually it requires a lot of experience to create any feasible schedule at all.

In the first part of table 1 some complexity-related factors are listed. It can be seen that highly complex structures can be found especially in the selected plants of companies A and E, and in some parts of company B.

A **high flexibility** in resource assignment arises from the use of multi-purpose resources, e. g. reaction tanks which in principle can be used for a broad variety of products and processes. However, usually there are restrictions concerning the resource's properties and additional equipment that is (or can be made) available with the resource. Scheduling complexity increases naturally with a **large number of** different **products**, because there are different requirements for each product. If there is a **large number of different paths** for each product, scheduling involves finding good paths so that the different jobs do not interfere with each other, and there are not too many idle units and the lead times are not too high. With a large number of **interdependencies between plants**, scheduling decisions of one plant affect other plants as well, i. e. there must be some kind of co-ordination mechanism (usually on business level), and there are restrictions which result from other plants' requirements.

Scheduling is more difficult when many changes have to be made. If there is **a high frequency of product changes**, the number of jobs to be scheduled is high, and a lot of cleaning procedures and set-ups have to be made. Another problem occurs when there are **frequent changes of the schedule** necessary. In this case, much re-scheduling has to be done, and it is even more difficult to find good schedules than without these frequent changes. When **entirely new products** have to be produced, test productions have to be made, and the process is not known so well in advance, so there are more uncertainties for scheduling.

Further process industry-specific restrictions that increase the scheduling complexity are discussed in the following paragraph.

4.2 Special Scheduling Problems and Requirements

The second part of table 1 lists several scheduling-related topics specific to the process industries. Not all of them are exclusive to the process industries, but in this area they are especially important.

In many companies, **campaigns** are scheduled rather than simple batches. Campaigns may consist of several batches of the same product which are produced in a non-interrupted sequence. During the production of a campaign, no changes in the resource configurations have to be made, and changeover and cleaning procedures are not (or only to a small extent) necessary. Campaigns may also contain batches of different products, which are sequenced such that cleaning and changeover times are minimised.

Changeover and cleaning times and costs are an important problem to most plants, and one of the main scheduling objectives is to reduce them. The changeover times also have to be considered for calculating the processing times that are used for scheduling.

For many products and processes, **alternative units** can be used, which are included in the different paths for a product. If the alternative resources are identical, times and other parameters stay the same when a job is moved to an alternative unit. However, when two different units can be used alternatively, several restrictions may change. At company B, for example, it is an important requirement for a scheduling system that it can handle **durations which depend on the unit** that is used. In some cases the process duration for one batch may be independent of its size (only the resource capacities are a limit for the maximum batch size), in other cases the **durations depend on the material quantities**, usually this dependency is non-linear.

In many plants it is possible to **change** the **unit configurations**. Such a unit configuration may include a reaction tank to which additional equipment is mounted according to the requirements of a specific job. To determine whether a certain job can be processed on a certain resource, its actual configuration has to be considered. Since with a change of products in some cases a change of unit configurations is required, it may be even necessary to schedule these configuration changes.

In the process industries many materials are pumped through pipes. If these pipes which connect different units are fixed, then they restrict the use of units, because if a batch has to be processed in two units in succession, these units must be connected. There may be also **changeable unit connections**, i. e. it is possible to connect units in different ways. For scheduling it has to be considered, which connections are possible, and if a required pipe is not needed elsewhere at the same time.

A typical problem within the process industries is the occurrence of **by-products**. Some products cannot be made without necessarily producing one or more additional products or intermediates. Usually these by-products are used for some other productions. For that reason, different production processes depend on each other, because the quantity of the by-product needed for a second process depends on the quantity of the first process' primary product. A correct schedule must be according to these dependencies, or it must be possible to store the by-product.

Even more important than in the discrete manufacturing industry are quality checks and laboratory tests. In several cases **quality-dependent production** was found, i. e. which production steps have to be done is decided during production after the quality of the intermediate product has been determined. This means that not all production steps and times are known in advance and no exact schedule can be made. If the laboratory or some test-device can be a bottleneck, then it is even necessary to **schedule quality-tests**. Sometimes the **production has to wait until the test results are known**. The durations needed for the tests must then be included in calculating the processing times that are used for scheduling.

For **unstable intermediate** products a maximum waiting time between two processes has to be taken into account. If there are **shared resources** in the plant, i. e. resources that can be used for more than one production at the same time, it must be ensured that the utilisation of such resources is smaller or equal 100%, and some other restrictions may apply, as well. There may be also **central shared resources** that have to be shared between different plants. If such a central resource is a bottleneck, the use of this resource must be co-ordinated between the plants.

There are units which have to be emptied and cleaned entirely before the next batch can be processed. On other units the charging of material may start before the preceding batch is completely finished, i. e. the two **processes overlap**. In company E it is necessary to consider the **status of a unit** for calculating the changeover times. This requirement has been mentioned only in one company, but it is a very demanding requirement, and similar cases may occur where unit configurations are changed frequently (see above).

In all companies with a more or less complex production structure, there are many uncertainties in the schedules. Usually these **uncertainties are levelled out with** big enough **buffers**. In most of the companies these buffers are considered as being too large and too expensive. If the quality of the schedules would improve, the buffers could be reduced.

4.3 Current Scheduling Situation

In all selected companies, scheduling is done mainly manually, only supported by the use of spread-sheet programs or manual gantt charts. Scheduling depends very much on **expert**

knowledge of people who know their plant very well. In many cases these people have worked in the plant for many years.

Many of the restrictions and dependencies for scheduling are not well documented. There are many **non-structured** restrictions which are known and applied rather intuitively by the scheduling experts. Without these scheduling experts - usually one person in a plant - the quality of scheduling would decrease significantly. For a scheduling system it would be necessary to structure all these restrictions and to represent them in the information system.

In most companies it is not tried to optimise or at least to compare different schedules. It even requires much effort to create at least one feasible schedule. In many cases it is necessary to communicate a lot with the business level or with other plants, thus creating the schedule iteratively. In these cases there is not much freedom for scheduling on the plant level, and the plant people's job is to tell the business level whether they can produce a certain order, rather than actively creating and optimising their own schedule.

The interview partners from most companies complained about a **lack of transparency** about what is currently going on in the plant and what is scheduled for the near future. That means, the schedule is usually not documented in a way that everybody feels that he gets all information he needs. This includes information about which effects the plant manager's decision has on other plants.

4.4 Integration of Production Planning and Scheduling

A critical point is the integration of plant level and business level, i. e. of long-term production planning and scheduling. **None** of the selected companies has an **integrated information system** including both levels. There are no clearly defined interfaces between these two levels. It is not ensured that the data of both levels are consistent. The lack of an integrated information system also makes **the co-ordination between production planning and scheduling difficult**. This is usually done by meetings and telephone calls.

In several companies there is the problem that the **capacities that are used for long-term-planning are very different from the actual resource capacities in the plant**. The resulting production plans are therefore not feasible. The reason for this difference is the difficulty of aggregating capacities correctly. With simpler production structures it may be possible to form resource groups on which certain products can be manufactured. The capacity of such a resource group is the sum of the single resources' capacities. However, with a complex production structure and many restrictions it is not possible to build non-overlapping resource groups. If there is a restriction saying that product A and product B must not be in the same plant at the same time, the plant's capacity for producing B is reduced to zero as soon as product A has been started to being produced, even if 90% of the plant's resources are idle. To handle such cases, business level would need to know all restrictions, which is not realistic since the amount of data would be too huge. If this situation could be improved, the orders from the business level would be more accurate and scheduling would be easier.

In some areas of company B there is not even much co-ordination done on business level, but the **plants have to do the co-ordination themselves by direct communication**.

4.5 Requirements for Scheduling Systems

In table 2 an overview over the most important requirements for scheduling systems is given. Some of these requirements can be derived from the discussion of scheduling-relevant topics and problems in the preceding paragraphs, and most of them have also been mentioned explicitly by the interview partners. It can be seen that the companies with a more complex production structure (A, B, E) also have more requirements towards a scheduling system.

Requirement	Company A Dyes	 B Chem.	 C EPS	 C Tens.	 D Seeds	 E Cig.
Comfortable graphical user interface	X	X		X		X
Transparency of current and future situation in plant	X	X		X	X	X
Make effects of decisions on other plants etc. visible	X	X		X		X
Simulation (what if-analysis)				X		X
All relevant restrictions must be in the system	X	X		X	X	X
Creation of feasible schedules	X	X		X	X	X
Consideration of changing unit configurations	X	X				X
Possibility for manual scheduling	X	X	X	X	X	X
System should create different proposals for schedule						X
Calculation and reduction of changeover and cleaning times	X	X				X
Updating schedule according to process feedback	X					X
Scheduling different resource types (e.g. units, labour, ...)	X	X				
Cost related evaluation of schedule	X			X		X
Co-ordination of different operations		X				
Integration into company wide information system	X	X			X	X
Link to laboratory information system (LIMS)	X	X	X	X		
Link to process control system	X			X		

Table 2: Requirements for scheduling systems.

One of the most important requirements for a scheduling system is **a comfortable graphical user-interface**, including a Gantt-chart. Only where the production structures are very simple, it is not required to display the assignments of jobs to resources graphically. Other views and diagrams to evaluate scheduling-related data should also be part of the graphical user interface. Such user interfaces are provided with many scheduling and Leitstand systems.

The graphical user-interface is needed to provide **transparency of the current situation in the plant**, as well as what is scheduled for the near future.

In several companies it would be appreciated to have a system that provides information not only about the situation in the plant, but also about related areas in other plants, so that it could be made **visible which effects a decision has on other plants**.

A scheduling system should also include the possibility to **simulate** scheduling decisions by creating one or more schedules that are not actually used but which show the effects of several decisions (**"what if-analysis"**). If the operator is not satisfied with such a simulated schedule, he can delete it and create a new one. If he likes a created schedule, he can release it for production.

A major requirement is that **all relevant restrictions must be represented in the system** and be taken into account for scheduling. Meeting this requirement will not be easy, since large parts of these restrictions are not documented so far, but it is necessary, because the system is required to **create feasible schedules**.

In some plants it will be necessary to **consider changes of unit configurations**. Otherwise it cannot be checked if a job can be carried out on a specific unit. In very specific cases it may be even desirable to schedule configuration changes.

All interview partners require that a scheduling system allows for **manual scheduling**. Even if the system could create very good schedules, the operators still want to have control about scheduling and be able to make decisions. Other requirements can only be found in a few plants, i. e. that the system should **create** automatically **several proposals for a schedule** from which the operator can chose the one he likes best.

Since changeover and cleaning times are very important to many companies, it should be possible to **calculate** such times with the system, and it should support the **reduction of changeover and cleaning times and costs**. In some plants it is also required that the data of the scheduling system can be **updated automatically according to actual data and times fed back from process level**, and thus keeping the system always up-to-date.

In one case it was mentioned that it would be nice not only to **schedule** primary resources, such as units, but also **other types of resources**, such as labour or the resources for quality checks, etc. For another company it is necessary to have a **co-ordination mechanism for operations** of different processes.

Scheduling should help reducing costs, a useful feature therefore would be a function to calculate a schedule's costs so that **different schedules could be evaluated** not only according to lead times or utilisation rates, but also **according to costs**.

Integration is a very important topic in all companies. This includes **the integration into a company-wide information system**, as well as to the **laboratory information system (LIMS)** and to the **process control system**.

5 Summary and Conclusions

In this paper the results of a study have been presented regarding scheduling in the process industries. Plants from five companies have been investigated, including the chemical industry, the food industry and the seed producing industry. The interview results have been presented in detail for each company, discussing the production structure, production planning, scheduling and special problems and requirements concerning scheduling.

These results have then been summarised and compared. Those scheduling aspects that are common to several plants or that are remarkable have been discussed, and an overview over the most important requirements for a scheduling system has been given.

During the study it has turned out that the main differences between the process industries and the discrete manufacturing industry can be found rather in the detail than in the general problems related to scheduling. The main tasks of production planning and scheduling are mainly the same, and the basic requirements for a computer-based scheduling system are also similar. Current approaches and information systems for planning and scheduling in the discrete manufacturing industry solve many of the problems that have been discussed in this paper. For example, the integration aspects are addressed by concepts like computer integrated manufacturing (cf. *Scheer 1990*), and today it is possible to reach a high degree of integration with standard software (cf. *Scheer 1989, pp. 261-263* and *Scheer 1994, pp. 398-399*). Leitstand systems offer very good graphical user-interfaces which could be also used in the process industries.

The differences may not be large, but the details are very important. If a plant manager has to deal with by-products or with fixed unit-connections, he cannot use a system which may be very powerful and user-friendly but which cannot handle these specific restrictions. Scheduling systems for the discrete manufacturing industry can be used as a starting point for developing systems for the process industries. The necessary changes may be small, but they have to be made, and they must solve the specific problems, or they will not be successful.

As it can be seen from the results of the study, scheduling cannot be seen as an isolated task, but strategies for integrating production planning and scheduling and for an integrated management of material flows and business processes through several plants must be developed for the process industries, like they are outlined in concepts like computer integrated processing (CIP, cf. *Loos 1993a; Kersting, Pfeffer 1992; Riemer 1990*).

None of the interview partners was interested in highly sophisticated scheduling strategies and algorithms, but rather in providing better information about the plant. A tool should ensure the feasibility of schedules and provide better co-ordination between plant level and business level. The designers of information systems for the process industries should concentrate on these requirements.

However, these problems can not be solved only by implementing process-industry-specific, integrated information systems. Especially questions concerning the vertical co-ordination between different planning levels as well as the horizontal co-ordination of different plants require also new organisational concepts (cf. *Remme, Allweyer, Scheer 1994*). Rather than merely implementing information systems and fixing existing organisational structures that are not adequate anymore, the task is to identify the core business processes, to restructure the business along these processes, and to support the business processes by process industry-specific software.

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