The complexity of scheduling in practice

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Introduction

Production scheduling, which is a part of the planning and control of individual production units, lies at the very heart of the performance of manufacturing organizations. The need for efficient scheduling has greatly increased in recent decades owing to market demands for product quality, flexibility and order flow times. However, although scheduling research activities have in the same period moved from purely academic exercises to serious attempts to solve real-world problems, successful implementations of scheduling techniques in practice are still scarce[1-6]. Moreover, most of the existing successful implementations have only been realized in highly controlled production processes such as mass-assembly and the (semi-)process industry. Therefore, in many companies, scheduling is still a typically human domain. However, the task of scheduling production units can become very complex. Humans are not very well equipped to control or optimize large and complex systems, and the relations between actions and effects are very difficult to assess. Hence, practitioners in production planning and control are often convinced that much can be improved with regard to manual scheduling.

This paper will focus on problems that are related to the complexity of scheduling in practice. Techniques and information systems based on these techniques are commonly regarded as means to improve scheduling. However, because of the complexity of scheduling in practice, implementing these systems has created many problems. Schedules based on these techniques are often changed by the scheduler or are not carried out exactly on the shopfloor; they are often based on a simplified representation of the shopfloor, and therefore are possibly violating constraints. Also, some techniques cannot account for disturbances without completely regenerating the schedule. This can lead to unacceptable response times and nervous scheduling behaviour. Because the quality of a schedule is very hard to assess, the advantages of a scheduling technique are hard to prove to schedulers and the operators on the shopfloor. Therefore, these techniques are easily overruled by the scheduler and the shopfloor operators. The specific strengths and weaknesses of human cognition are often underemphasized when implementing scheduling techniques.

International Journal of Operations & Production Management, Vol. 16 No. 10, 1996, pp. 37-53. © MCB University Press, 0144-3577

In this paper an overview of the problems related to the complexity of scheduling in practice is given. Subsequently, alternative suggestions to improve scheduling are proposed. First a description of scheduling and how it relates to planning and sequencing is presented. Then a description of problems that cause the scheduling function in practice to be very complex, and also an overview on shopfloor models and scheduling techniques are given. Only dimensions of techniques and models relevant to the discussion are given. In the next section the problem of measuring performance of schedules is discussed. Then possible solutions to the problems discussed are provided. Lastly, the conclusions are presented.

Planning, scheduling and sequencing

In the literature, often a distinction is made between planning, scheduling and sequencing. However, clear definitions for each of these functions are difficult to find, which holds especially for the demarcation between planning, scheduling and sequencing. In this section, planning, scheduling and sequencing are discussed.

In production planning (for example material requirements planning (MRP)) the required level of production in a specified time horizon is determined[7]. Typically, the output of planning consists of material requirements in time. These requirements are passed to the lower control levels, i.e. scheduling. So, the output of planning, i.e. material requirements in time, is the input of scheduling. Production scheduling focuses on the allocation of finite resources to fulfil material requirements within individual production units. A production unit is an outlined part of the production process, which in the short term is self-contained regarding the use of resources[8] (note: production unit and shopfloor are used as equivalent terms in this paper). Scheduling is defined by Vollmann *et al.*[9] as: “a plan with reference to the sequence of and time allocated for each item or operation necessary to complete the item”. Hence, scheduling determines for each resource (which is in many cases only machine capacity) the points in time when operations are executed, under the following constraints:

- finite capacity resources;
- precedence relations (i.e. routeings);
- start dates and due dates of jobs.

These constraints, which are satisfied by scheduling, are not necessarily satisfied in the planning function. Scheduling should optimize (or at least satisfy) certain goals that are deduced from organizational objectives, for example, service level; resources utilization; set up costs; inventory costs; and order flow times. After scheduling, the schedule is transferred to the production unit. The implementation of a production plan or schedule is often referred to as dispatching[7].

At each workstation in a production unit, every time a job is completed, a decision has to be made about which order will be processed next; this decision is referred to as sequencing. The existence of an explicit sequencing decision on the shopfloor depends on how scheduling is carried out. Therefore a distinction is made between two possible aggregation levels of scheduling:

(1) *Resource level*. Jobs are scheduled for each resource (workstation). This type of scheduling gives no sequencing decision freedom to the shopfloor.

(2) *Production unit level*. Jobs are only scheduled for the total production unit. The operations of the job are not scheduled. This type of scheduling leaves the sequencing decision to the shopfloor.

So, if the schedule is made at the resource level, the production schedule contains a specific sequence. In this case, if the schedule is carried out literally, no separate sequencing decisions have to be made. However, if the schedule is made on the shopfloor level, all sequencing decisions are left to the shopfloor.

The theoretical relation between planning, scheduling and sequencing can be depicted as shown in Figure 1. According to theory, planning controls the inventory points in the goods flow and gives material requirements to scheduling. The scheduling function then releases jobs to the shopfloor. Dependent on the level of scheduling, sequencing decisions are made on the shopfloor. However, such a decomposition ignores a part of the complexity of scheduling in practice. First, especially in discrete product manufacturing, the co-ordination of jobs between production departments is rarely carried out adequately by planning. The planning function here usually consists of an MRP-type system. One disadvantage of MRP is that it often creates capacity problems within time buckets. To solve these problems, schedulers often have to consider jobs among preceding and following production units to smooth capacity demand. Second, if problems occur with specific jobs, schedulers have to know where the work came from and where it will go, to communicate about, for example, quality problems or delivery times. This level of co-ordination

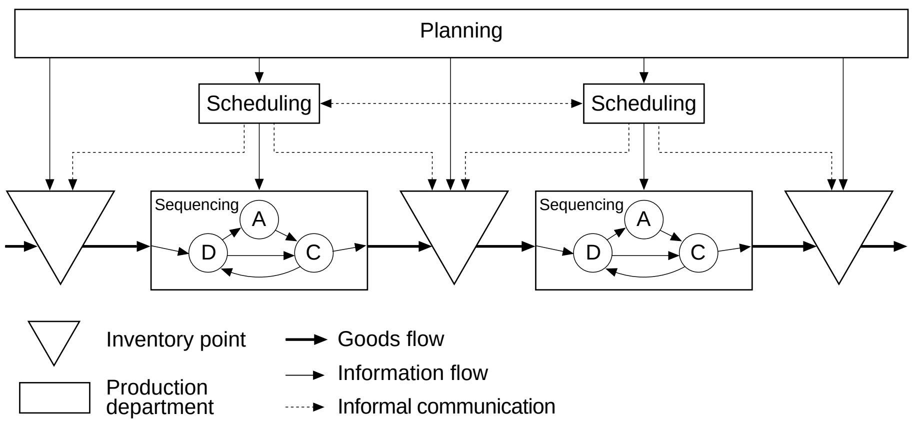

Figure 1. Planning, scheduling and sequencing

cannot be achieved by the planning layer, because an extensive knowledge of the specific job and the situation on the shopfloor is required. Therefore, schedulers within different departments often communicate with each other to co-ordinate the goods flow. This co-ordination is depicted by the dashed line between the scheduling functions in Figure 1.

In theory, the planning layer co-ordinates the inventory points in the goods flow. However, the inventory information of the planning layer is based on the planned production, which can be unreliable. Therefore, in practice, schedulers always check material availability before releasing orders to the shopfloor. They also check the inventory level of the end products of the production unit to determine whether production can be postponed, whether jobs can be split, or whether production is necessary at all.

Scheduling in practice

Disturbances

In practice, the planned or expected performance of production units often deviates from the actual performance. Most of these deviations are negative, which means that the actual performance is worse than the expected performance. Apparently, expectations about future performances are often too optimistic. On the shopfloor, many everyday disturbances occur which cause these performance deviations. These disturbances can be divided into three categories:

(1) disturbances regarding the capacity;

(2) disturbances related to orders;

(3) disturbances related to the measurement of data.

An overview of disturbances, which is by no means exhaustive, is given in Table I. These disturbances are discussed below.

A general characteristic of the first two types of disturbance is that they are unexpected. Therefore, other occurrences that may influence the performance negatively (such as vacation and training of operators, and preventive

Type of disturbance	Examples
Capacity	Machine breakdowns Illness of operators Unavailability of tools
Orders	Unavailability of materials and drawings Fulfilment of sequencing rules Extra orders caused by scrap, rework Rush orders
Measurement of data	Differences between pre-calculated and actual processing time Capacity efficiencies

Table I.
Common disturbances

maintenance) are not considered to be real disturbances because they can be taken into account by a scheduler.

Capacity disturbances can be divided into disturbances caused by machine capacity (e.g. machine breakdowns), disturbances caused by operator capacity (e.g. operator illness), and disturbances caused by tool capacity (e.g. unavailability of specific tools). Often, capacity disturbances cause real problems regarding the performance of production units. Immediate solutions must be found in the use of operator flexibility[10] and the use of alternative routeings.

Order-related aspects that delay the progress of individual orders are, for example, the unavailability of raw materials and order-specific drawings. Although in many production departments a sequencing rule is used, which is often quite simple, operators may deviate from this rule, and thereby influence the performance (especially the performance measures directed at time, e.g. delivery reliability). If scheduling implicitly defines a sequence, as has been stated in the previous section, the fulfilment of the schedule will also be influenced by these behaviour deviations. The underlying decision behaviour will be discussed later. Another example of an order-related disturbance is the arrival of rush orders. These orders delay the expected progress of the other orders that have already been released to production. An example of an order-related disturbance is the extra work that has to be scheduled due to scrap. Sometimes, the expected scrap is taken into account (e.g. by enlarging the order lot sizes) but the actual scrap can be quite different, just as occurs in processing time deviations.

An example of a disturbance related to the measurement of data is that of processing times estimated by the work preparation department. Schedulers confronted with significant processing time uncertainty often discover that a schedule which is optimal with respect to a deterministic or stochastic scheduling model yields quite poor performance when evaluated relative to the actual processing times[11]. This type of a disturbance can often be found in engineer-to-order companies because of the lack of historical data about processing times of newly developed products or components. The determination of capacity efficiencies is another example of the problematic measurement of data. A cause for this specific problem is that the definition of capacity is often unclear[12].

The disturbances related to the measurement of data are not considered further in this paper because it is a type of disturbance for which a production unit cannot be held responsible. Solutions for this type of problem must be found in other departments, such as the work preparation department. In our experience, most of the above mentioned disturbances are known to practitioners. Often, the other types of disturbance are qualitative in nature rather than quantitative, which makes it difficult to validate the effect of a specific disturbance on performance. This will be discussed in more detail in the next section.

Techniques

The research in production scheduling has led to many techniques. Some of these techniques are commercially available in software packages[13]. However, because of the complexity of scheduling in practice, many implementations of techniques have not resulted in the expected improvements. A large number of scheduling techniques, and information systems based on these techniques are available. An overview of techniques can be found in [14]. The types of techniques relevant to this paper are:

- *Priority dispatching rules*. Priority dispatching rules are usually based on job characteristics, e.g. processing time or due date. Some rules also take the status of the total shop into account, i.e. workload. An example of a dispatching rule is the shortest processing time (SPT) rule (i.e. if a job is completed at a workstation, the job with the shortest processing time in the queue will be processed next). Priority dispatching rules can be executed by the scheduler or on the shopfloor. If the scheduler uses these techniques, the shopfloor is simulated by a time-clock, and operations are scheduled according to the priority rule. If the operators on the shopfloor use these techniques, the decision about which order to select next from the queue for the workstation if an order has been completed is based on the priority rule.
- *Search techniques*. These techniques find an optimal schedule by enumerating many (possibly all feasible) schedules and choosing the best one according to a specific performance criterion, e.g. makespan, average order flow time. Examples are: branch and bound techniques, and mathematical programming.
- *Bottleneck methods*. These techniques make a distinction between bottleneck and non-bottleneck resources. The bottleneck resource is scheduled first to ensure maximal utilization. Then the critical non-bottleneck resources, i.e. resources preceding the bottleneck, are scheduled to provide the bottleneck continuously with work. A well-known example of a bottleneck technique is optimized production technology (OPT).
- *Knowledge-based techniques*. Knowledge-based techniques model the shopfloor by means of many hard and soft constraints. These rules are often obtained by eliciting knowledge from (experienced) schedulers. These techniques are usually aimed at generating feasible schedules[15].

Scheduling techniques can be described by two dimensions: the model of the shopfloor that is used, and the scheduling process employed. These factors will be discussed below.

Model of the shopfloor. Techniques rely on a certain model of the shopfloor to generate a production schedule. This model is based on the structure of the shopfloor, i.e. machines, tools, personnel. However, because of the very complex and dynamic nature of shopfloors, often many assumptions have to be made to enable economically feasible modelling. An example of such an assumption is that jobs cannot be split. However, in practice, jobs often can be split and produced simultaneously on two or more machines (and possibly the second machine needs a longer processing time). In this case (and similar cases), the scheduler or the shopfloor workers will probably violate the schedule and split jobs if necessary.

If techniques generate schedules that are based on an invalid model of the shopfloor, these schedules have to be adjusted manually. However, if the schedule is adjusted manually, the performance criterion on which the schedule was based will suffer from these actions, and the reason for using such a technique becomes doubtful. Priority despatching rules suffer less from this problem, because these techniques do not necessarily rely on a model of the shopfloor. Instead, they can be executed by operators on the level of workstations.

Problems related to the model of the shopfloor occur especially with search techniques. Although it is theoretically possible to model the shopfloor in great detail, the level of detail has to be paid by the response time of the scheduling process and the costs of the modelling efforts. Knowledge-based techniques (KBTs) are only slightly more successful in modelling the shopfloor. The strength of KBTs, i.e. to model many hard and soft constraints of the shopfloor, also comes with weaknesses. Because these rules are constantly subject to change, the knowledge elicitation and modelling process will practically never end. Also, because KBTs are usually based on knowledge elicited from human schedulers, they only duplicate human performance and cannot create a better schedule than a human scheduler. Moreover, KBTs also suffer from long response times if a detailed model of the shopfloor is used.

Scheduling process. As has been discussed above, many disturbances occur on the shopfloor. Therefore, schedules have to be adjusted frequently. However, some techniques do not offer the possibility to adjust the schedule manually. Instead, each time something relatively small occurs, the technique generates a complete schedule. Techniques that are able to generate only a complete schedule usually suffer from the "final-state" problem[13]. This means, that a small change in the status of the shopfloor causes major changes in the production schedule. For example: job X has been scheduled to start on Monday at 10.00 a.m. However, the material required for job X is not present, so it cannot be started. To keep the schedule up to date, job X has to be rescheduled to a later start time in the schedule. The schedule technique now calculates a new optimal schedule with job X rescheduled. This new optimal schedule is totally different from the "old" schedule.

In many production units, disturbances, such as in the example just given, happen every few minutes. If a schedule generation technique were used here, the system may generate a completely new schedule every few minutes. The scheduler and the personnel on the shopfloor would not accept such "nervous" behaviour and eventually would reject the constant load of schedules.

A priority dispatching rule can be executed manually on the shopfloor and is thereby much more robust than techniques of the second category, which are executed on a higher organizational level. If despatching rules are used on the shopfloor, no fixed sequence is present, and each time a job is completed at a machine, the shopfloor worker will choose the next order according to the priority despatching rule. Also, if the shopfloor worker decides to deviate from dispatching rules, this does not have major consequences on other jobs in the shop. So, dispatching rules enable employees to use their own mental model of the shopfloor.

Of the techniques discussed, priority dispatching rules are the most broadly used in practice. Also, these priority rules often belong to implicit scheduling guidelines that schedulers already use, unaware of their meaning in production planning and control theory. However, priority dispatching rules are not very "smart" and they generate schedules that are far from optimal with respect to a specific performance criterion. Most of these rules use local information (at the workstation level), which leads to local optimization, i.e. insensitive to the overall state of the production unit. Mathematical techniques give the best results if we solely look at the ability to optimize schedules conform one or a combination of performance criteria. Bottleneck techniques focus primarily on the utilization of bottlenecks and are not very well suited to optimize schedules to conform to other goals. Knowledge-based techniques are not used in the first place to optimize schedules, instead they are able to generate a schedule that is a feasible conform to the many constraints in the knowledge base.

Human factors

As has been stated previously, scheduling is still a manual task in most companies. Because some elements of scheduling are very hard to automate (e.g. negotiating with suppliers about delivery dates), humans will probably continue to play a key role in scheduling for a long time. The human role in scheduling has been studied in various laboratory experiments and some field studies[16]. An important lesson to be learned from past studies is that the question–which is "better", man or machine scheduling?–is not relevant. Designers of scheduling techniques should take into account that human cognitive abilities fit well with some elements of the scheduling task, while other elements cause difficulties. The weaknesses and strengths of the cognitive abilities of humans are outlined here.

Limited cognitive abilities. The *short-term memory* of humans applies to the amount of information that a human can pay attention to simultaneously. A human can have approximately seven "chunks" of information in his or her short-term memory[17]. One information chunk can apply to one or a coherent set of task elements. To manage all task elements in the scheduling task, the task should be regarded on a certain level of aggregation to conform to the limited capacity of short-term memory. A high aggregation level would be to look at all jobs simultaneously and not discriminate between groups or individual work orders. A low level of aggregation would be to look at each task element separately, for example, each job. It will be clear that the first option is not suitable for manipulating the jobs in the schedule. The last option violates the short-term memory constraint. However, no in between levels of decomposition are available. When constructing a schedule, one has to take into account that an action regarding one job influences most other jobs. However, the human scheduler is forced to decompose the task anyway. This results subsequently in sub-optimizing parts of the schedule, and the human is therefore not able to optimize the schedule towards some performance criterion.

The *long-term memory* of humans is, contrarily to the short-term memory, not limited regarding capacity. Limitations of long-term memory lie in our restricted ability to *recollect* information[17]. These restrictions especially apply to abstract and numerical information. The limitations of the long-term memory of humans has an effect on the ability to assess effects that occur as a result of actions with some delay. As a result, the human scheduler is not able to assess the effects of his or her actions, and to balance actions aimed at the short term and actions aimed at the long term. Also, the human is unable to learn how to improve his or her performance because the schedule performance cannot be evaluated. The problem of performance evaluation will be discussed in more detail in the next section.

Advanced cognitive abilities. Humans are very well equipped to cope with many "soft", qualitative task elements. Humans are superior to existing scheduling techniques and information systems regarding the following characteristics[6]:

- *Flexibility, adaptability and learning*. Humans can cope with many stated, not stated, incomplete, erroneous and outdated goals and constraints. Furthermore, humans are able to deal with the fact that these goals and constraints are seldom more stable than a few hours.
- *Communication and negotiation*. Humans are able to influence the variability and the constraints of the shopfloor; they can communicate with the operators on the shopfloor to influence job priorities or to influence processing times. Humans are able to communicate and negotiate with (internal) customers if jobs are delayed, or communicate with suppliers if materials are not available as planned.
- *Intuition*. Humans are able to fill in the blanks of missing information required to schedule. This requires a great amount of "tacit knowledge". At the time of collecting this knowledge it is not always clear which goals are served by it.

Use of techniques. The success of techniques in practice is ultimately determined by their use by humans. Therefore, we should ask ourselves what the determinants of the use of techniques by humans are. The following should be noted with regard to the transparency of techniques. The issue of transparency or opaqueness of techniques is often referred to as the black box problem in literature from an operational point of view. However, for the use of techniques by humans, the *perceived* opaqueness should be considered. Therefore, transparency is discussed from a psychological point of view.

Humans often prefer their own judgement to the application of techniques. A common explanation is that humans know that these techniques are imperfect and they expect–possibly erroneously–that increased mental effort will increase performance. This especially goes for situations where humans are confident about their expertise[18]. How much confidence depends on how much expertise is necessary to fulfil the task. The scheduling task requires a high level of expertise; schedulers usually know the ins and outs of the shopfloor (e.g. see [19]).

Human confidence in techniques can be improved by offering feedback in which the actual performance is compared with the performance that would have been realized if the rule had been used. A somewhat less effective measure is to describe explicitly the performance characteristics of the rule to the human schedulers, which makes the rule more transparent[20]. If it is not clear how a technique finds a particular schedule, the scheduling technique is opaque to the scheduler.

Offering the feedback mentioned is not possible in the scheduling task, as the performance of schedules often cannot be measured objectively. Therefore, the only way to improve use of techniques by humans is to increase transparency. The transparency of a decision rule is especially important in situations where the human scheduler has to interact with the technique to solve problems. If it is not clear for the scheduler how to interact with the technique, the human scheduler will be less inclined to use it. This especially goes for situations where humans are in stressful situations. In these situations, humans want to be in complete control of the situation, thereby increasing their workload[21]. Stress often occurs in tasks with constrained time, which is the essence of the scheduling task.

Making the system more transparent to the scheduler can be achieved by using simple decision rules, and by offering support that enables the human scheduler to monitor, adjust and implement schedules. Electronic Gantt charts have been demonstrated to improve performance of scheduling tasks where much information would have to be integrated mentally[22]. On the other hand, in scheduling tasks with few task elements, electronic Gantt charts would be counterproductive, as the information would be presented here on a aggregation level that was too high, and the human would have to decompose this mentally. Therefore, the information presentation requirements should be adequately matched with the scheduling process.

Execution of the schedule. Defining a detailed schedule assumes that the schedule is carried out exactly in the production unit. However, operators in the production unit will circumvent the schedule if disturbances cause the schedule to become invalid. Some researchers and practitioners claim that a lack of schedule discipline is a major cause of problems regarding execution of the schedule (see, for example, [23]). From an operations managerial point of view, as much control as possible should be “squeezed” out of the production unit to the scheduling layer to optimize the production process. However, from a social and motivational point of view, the operators on the shopfloor should be able to exercise some control over their work, and some companies therefore explicitly allocate control functions to the shopfloor.

Experience teaches us that forcing operators to carry out a schedule exactly does not prevail in companies where humans are involved in the production process, and where operators do not have other control tasks, such as supervising an FMS (see, for example, the case studies described in [24] and [25]). Therefore, in these companies, some decision freedom should be allocated to the production unit. If consensus is achieved about a clear division of responsibilities, the effects of scheduling decisions taken by the operators on the shopfloor are mostly not felt by the scheduler and therefore do not require rescheduling actions taken by a human scheduler. The case study described later on in this paper presents an example of a company where a clear definition of responsibilities has been achieved.

Performance

In the previous section the reasons for the complexity in scheduling in practice were discussed. Another problem regarding scheduling in practice will be discussed in this section: assessing schedule performance, and offering feedback to schedulers.

Assessing schedule performance

The problem of measuring schedule quality has only recently been recognized as a very complex problem[26]. Examples of possible performance criteria that already have been mentioned in this paper are service level and inventory costs. However, in practice, a single performance criterion is never used, and a compromise has to be made between multiple performance criteria. To assess the quality of a schedule objectively, the normative performance of the shopfloor needs to be known. However, it is not possible to calculate this normative performance. Therefore, quality measures always have to be relative, i.e. compared to past performance. Because manufacturing systems are seldom stable, the comparison of performance variables in time can be heavily biased.

In many production organizations, the performance criteria for the production planning and control function focus on service level, while also keeping costs under control. These performance criteria should then be used when making plans, schedules and sequences. However, the more the planning and control function is decomposed into different horizons, layers and chains, the more difficult it is to relate the variety of sub-goals with the overall goal.

First, when measuring the quality of a schedule, the question arises which time horizon should be evaluated. If a specific time horizon is chosen, the possibility exists that a positive performance in the current schedule effects a negative performance in the coming periods. Because of common fluctuations in the performance of the shopfloor there are periods where the performance is higher than the planned long-term performance, and there will also be periods in which the performance is lower than the planned long-term performance. According to these natural fluctuations, decisions aimed at compensating negative deviations in the short term are often superfluous. Such decisions can be judged exaggerated and costly because performance will return to the average level all the same[27].

Second, in practice, the different organizational levels of production planning and control have grown to work with different and possibly conflicting performance goals. Regarding performance, typical norms are: delivery reliability; capacity utilization; inventory levels; order flow times. Of course, these norms cannot all be fulfilled at the same time. For example, a well-known conflict between performance measures is the trade-off between utilization level and order flow time. Such a conflict can occur between the scheduler and the shopfloor manager. The scheduler is generally responsible for delivery reliability, while the shopfloor manager generally is responsible for the throughput and the capacity utilization of the shop. These two goals are clearly in contrast with each other.

Third, it is possible that a scheduler of a particular production unit improves the production unit's performance at the cost of the performance of other production units.

Feedback

A result of the problem of assessing schedule performance is that it is not possible to offer adequate feedback to schedulers or shopfloor workers if schedule performance cannot be measured adequately. We think that this problem is the root cause for the fact that in practice many schedulers are not interested in feedback about their actions. Schedulers usually try to minimize the amount of angry phone calls, and do not think that they are able to influence overall performance. In many organizations, the scheduler feels that the performance of the shop is beyond his or her control and improving this intangible performance by means of a technique does not appeal to them.

Successful scheduling: a case study example

A case study is now given which illustrates how techniques and information systems can be used to improve scheduling. The case study has been carried out in a corrugated board plant. The production process in this company can be divided in two parts: first, corrugated board is produced from rolls of paper, and cut and slit into sheets of board. Approximately 30 cardboard qualities are produced from approximately 25 qualities of paper. In the second production step, boxes are produced from these cardboard sheets. The company employs a make-to-order strategy; the end-products are customer specific. Two types of scheduling techniques, incorporated in information systems, are used to generate schedules:

(1) *Cardboard sheets production.* Scheduling of the cardboard sheet production unit comprises two aspects. First, work orders with the same cardboard quality are clustered. These quality clusters occupy a fixed place in a cyclic production schedule. Second, within the clusters of work orders, slitting and cutting of that specific quality of cardboard into cardboard sheets is optimized by scheduling which is carried out by a branch-and-bound search algorithm to minimize material waste.

(2) *Box production.* The second part of the production process is scheduled by an electronic Gantt chart with priority rules. The jobs are sequenced by the EDD (earliest due date) rule. The scheduler often reschedules jobs manually.

The aspects of scheduling complexity in practice which have been discussed will now be evaluated for the company in the case study.

Performance goals

We have mentioned before that assessing schedule performance is a very complex problem. For the first part of the production process, i.e. board production, cutting and slitting, this problem has been solved partly by optimizing material waste within product qualities. The optimality of the cyclic production scheduling method is unclear. However, the cycle is relatively short compared to the throughput time, and fast-moving product qualities are produced once a day at least.

An outstanding feature of the company is that the different organizational levels all work towards meeting due dates. Departmental goals that oppose each other in many other companies are solved by a clear division of responsibilities and decision freedom. For example, the sales department and operations management are linked through a separate department called "sales support". This department guards sales quota, checks detailed capacity and negotiates about delivery times. The operators on the shopfloor have the freedom to choose jobs from the schedule within a horizon of one day. Technically, it may have been possible to schedule on a more detailed level, and thereby to squeeze all decision freedom from the shopfloor towards production scheduling. However, the personnel management of the company gives priority to offer people responsibilities of their own. Forcing operators to carry out a detailed schedule exactly does not fit in this strategy.

Disturbances

Disturbances, which are especially present in the second part of the production process, have been dealt with by the corrugated board company in three ways:

(1) by restructuring the products and production;

(2) by giving decision freedom to the machine operators;

(3) by realizing effective human-computer interaction.

First, the amount of board qualities has been standardized to approximately 30 qualities. These qualities are made by (combinations of) 25 different qualities of paper. More flexibility is put in the production process by multi-deployment of operators, creating possibilities for alternative routeings, and automated changeovers. Second, if disturbances occur, the machine operators can react themselves within the horizon of one day. If a disturbance reaches beyond one day, rescheduling has to take place. Third, because of the transparency of the system this can be carried out very easily by the scheduler. The system uses priority rules to schedule work orders according to due dates, which is easy to understand by the scheduler. Furthermore, the scheduler can manipulate the schedule using the graphic-interactive user-interface.

Human factors

The reason for applying a technique in scheduling lies in the cognitive weaknesses of human schedulers. Sub-tasks within scheduling that require the handling of many homogeneous jobs, procedures, capacity constraints, etc., to optimize specified performance criteria should be supported by techniques. Cognitive strengths should be employed for sub-tasks that are difficult to incorporate with techniques. The reason for allocating sub-tasks to the scheduler or to the operators of the shop lies in the cognitive strengths of humans, which are especially employed in production units where scheduling tasks require flexibility, communication and intuition. The interaction between techniques and humans should enable the human scheduler to handle these sub-tasks.

In the first part of the production process of the corrugated board factory, tasks that require abilities that belong to the cognitive weaknesses of humans, i.e. handling many homogeneous elements simultaneously, are carried out by the system. The algorithm optimizes the cutting and slitting problem by enumerating all possible solutions and choosing the best one, with a processing time of approximately one minute. The cognitive strengths of humans are used to evaluate the solution and occasionally to adjust the production cycle. Also, the solution is communicated informally with the scheduler of the second part of the production process.

In the second part of the production process of the corrugated board factory, the cognitive strengths of humans are employed to handle exceptions in the production schedule. Manipulating large numbers of non-exceptions belongs to the cognitive weaknesses of humans and, therefore, these are handled by the system. To enable the human scheduler to handle the exceptions in an adequate way, the system offers the user an overview of the status of production. Manipulation of exceptions is enabled by the graphical interactive user-interface; with the mouse, the scheduler can move jobs in the schedule.

Feedback

In the corrugated board company, the performance of the cutting and slitting process, i.e. material waste, is strictly guarded by the scheduler. If the material waste rises beyond a certain level, the production cycle is reconsidered and jobs are moved if possible. The performance of the box production process is not evaluated in an aggregate way. The scheduler is only interested in detailed feedback about exceptions and does not evaluate aggregate measures such as the service level. Or, as one scheduler put it: "I am not familiar with or interested in the service-level achieved by the production unit I schedule. I just schedule jobs. What becomes of it is beyond my control". The evaluation module of the information system is therefore not used at all.

Conclusions

Implementing scheduling techniques and information systems often results in disappointment by shopfloor management and schedulers themselves. A number of causes have been given why scheduling techniques often do not work in practice. These causes are summarized below:

- *Disturbances,* such as machine breakdowns, rush orders, and the unavailability of raw materials result in differences between the generated schedule and the actual status of the production unit. In these cases operators often circumvent the schedule.
- The model and schedule generation process of a *technique* have to match the structure and dynamics of a production unit. If the model of a technique does not represent reality, additional checks and changes have to be made by the human scheduler. If the schedule generation process of a technique does not match the dynamics of the production unit, the human scheduler has to update the schedule manually. These problems may result in the human scheduler not using the technique.
- *Humans* may overrule the scheduling technique because they think that they can outperform the technique by increased mental effort.
- *Goals* of mutual dependent organizational functions may conflict with each other. Also, long-term goals may collide with short-term goals. If a scheduling technique does not adhere to the organization's goals there is a large chance that it will not be used.

To tackle the problems mentioned above several suggestions have been made. These suggestions were illustrated with a case study. The suggestions are summarized below:

- *Goals.* An organization should state clear priorities in how to achieve various goals such as utilization and delivery times. Conflicts between goals are often solved by means of negotiation. Because negotiation cannot be carried out by means of techniques, a technique should rely on a human scheduler. In the case study this was realized by allocating a bucket of one day to the shopfloor operators. Responsibilities between sales and operations management were co-ordinated by means of an intermediate sales support department. Performance feedback, which theoretically can be used to improve the scheduling system's use, was not used by either the scheduler or the operations management.

- The production unit *model of a scheduling technique* should match the specific characteristics of the production unit. In the company described this was not a large problem as customized software had been built. Moreover, by allocating a bucket of one day to the shopfloor, the technical intricacies could be hidden from the scheduler.
- The *schedule generation process of a technique* should not assume to be able to control production by the minute. The scheduler is able to use a variety of scheduling rules that enable him to define easily the bucket of one day.
- The *use of techniques by humans* can be improved by making techniques transparent for users. Moreover, a human scheduler will be very pragmatic in using techniques; if he thinks that it will cost more effort than can be gained, a technique will probably be ignored. Prototyping and user participation can be used to improve the (perceived) value of a system.
- Last but not least, sources of disturbances should be reduced as much as possible. This was primarily realized by simplifying the material flow, i.e. reducing the amount of raw material types to 25 and the amount of cardboard types to 30. Also, many technical improvements have been made.

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