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Wiers, V.C.S.

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A Review of the Applicability of OR and AI Scheduling Techniques in Practice

VCS WIERS

Eindhoven University of Technology, Eindhoven, The Netherlands

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This paper presents a review of the applicability of scheduling techniques in practice. Both the operations research and the artificial intelligence research communities have produced a number of reports on the applicability of techniques, often in isolation from each other, although the problems encountered seem largely similar in each case. Moreover, studies on the role of humans in production scheduling are reviewed. Papers that discuss the use of techniques by humans are also discussed. The paper suggests ways in which the applicability of scheduling techniques might be improved. © 1997 Elsevier Science Ltd

Key words—scheduling, operations research, artificial intelligence, applicability of techniques

1. INTRODUCTION

SCHEDULING CAN GENERALLY be described as allocating a set of resources over time to perform a set of tasks. Scheduling emerges in various domains, such as nurse scheduling, aeroplane landing scheduling, train scheduling, production scheduling. This paper focuses on the latter, i.e. production scheduling. In production systems, scheduling typically concerns allocating a set of machines to perform a set of work within a certain time period. The result of scheduling is a schedule, which can be defined as: a plan with reference to the sequence of, and time allocated for each item, or operation necessary to complete the item [1].

Much has been written about scheduling problems in the last few decades. Yet, in spite of the vast body of research, and the fact that many practitioners in operations management are convinced that manual scheduling is highly capable of improvement, implementations of scheduling techniques in practice are scarce. Until recently, the lack of innovation in industrial production scheduling could be attributed to the fact that much of the scientific research had been aimed at strongly simplified problems which were not representative of practice, e.g. small-sized problems, deterministic arrival and processing times. However, today academia has moved its focus to real-world problems, and many scheduling techniques are now available in standard software. The number of software packages at hand for production scheduling appears to rise by the day. However, in spite of the large amount of available techniques, successful implementations of these techniques are limited.

To improve the applicability of scheduling techniques in practice, it is necessary that we learn from shortcomings of techniques identified by others. However, a major shortcoming of scheduling research is that it is widely dispersed over many research communities and journals. Therefore, we aim to give an overview in this paper of the research done on the applicability of techniques in practice. Moreover, the research on the human factor in scheduling will be reviewed, for two reasons: firstly, humans are still the key element of scheduling in practice, and secondly, the success
of failure of techniques in practice depends on their use by human schedulers.

The paper is structured as follows. In Section 2, papers on the applicability of techniques from operations research will be reviewed. In Section 3, papers on the applicability of techniques from artificial intelligence will be reviewed. In Section 4, research on the human role in scheduling will be discussed. In Section 5, motivational factors of the use of techniques by humans will be reviewed. In Section 6, the effectiveness of various types of displays will be discussed. Lastly, in Section 7, a discussion of the literature is given.

2. THE APPLICABILITY OF OR TECHNIQUES

From its emergence at the beginning of this century, scheduling has generally been perceived by academia as a mathematical problem. Hence, research on scheduling has primarily been the domain of operations research. The amount of reported research on scheduling in the operations research community is immense. The intention here is not to give a review of scheduling in general: a review of single-machine research can be found in [2], a review of dynamic scheduling research can be found in [3], and heuristic scheduling systems are treated in [4].

To enable modelling and solving the problem in a mathematically feasible way, many researchers greatly simplified the scheduling problem. It turned out that analytical solutions to the scheduling problem were infeasible for problems of any complexity. Therefore, problems were assumed to be deterministic and static, only a small number of resources and operations were considered, constraints and relations were ignored, etc. These assumptions greatly reduced the applicability of techniques in practice. King [5] was one of the first who explicitly recognized the gap between theory and practice in production scheduling. King attributed this gap to the oversimplification of complex real-world situations so as to enable the construction of mathematical models. In his well-known review article about production scheduling, Graves [6] also addressed this problem, and stressed the need for research on the following six problems, which are still highly relevant today: performance measurement of production systems; robustness in scheduling; interaction between scheduling decisions and other types of organizational decisions; data availability and accuracy; specialized scheduling functions such as expediting; scheduling of computerized manufacturing systems.

Another aspect that hampered the implementation of scheduling techniques in practice was that for a number of decades, scheduling techniques needed too much computing power. Most of the scientific research had been directed towards relatively small-scale optimization programs that are highly iterative. Contrarily, nearly all software suppliers considered iterative algorithms to be very risky. For builders of software who have to retrieve each single record from a disk there was only one overall guideline: avoid any situation in which a record can be addressed more than once [7].

Two recent developments, therefore, seemed promising for the applicability of scheduling techniques in practice. Firstly, with the arrival of cheap computing power in the 1960s an important obstacle for the application of scheduling techniques in practice seemed to disappear. Secondly, where scientific research initially focused on greatly simplified problems, it now moved to solving problems that more closely resembled real-world settings. With integer and dynamic programming techniques, rather realistic scheduling problems could be modelled and solved. Heuristic search algorithms were introduced that were able to find (near-) optimal schedules from a large amount of feasible schedules [4]. As these algorithms became "smarter" they were better able to find a good solution within a reasonable amount of time using computers.

However, despite these developments, the impact of academia on industrial scheduling remains small. From various reports in the literature, it can be concluded that the complexity and instability of production systems are still underestimated in many scheduling techniques. A survey by Halshall et al. [8], on the use of scheduling techniques and information systems in smaller manufacturing companies in the UK, shows that the scheduling process is greatly facilitated by a stable and predictable environment, and that uncertainties need to be taken into account when designing a scheduling system. Also, a scheduling system should be able to revise only the affected parts.
in the schedule in case of disturbances and to check if the resulting schedule is feasible.

Problems regarding the applicability of operations research techniques are also discussed by Buxey [9], who reviews the role that operations research has played in production planning and scheduling. He concludes that where operations research has tried to optimize one stage of a hierarchical system, e.g. the production unit, it has had little impact. Four reasons are given for this: (1) the complexity of the problem; (2) the interdependence of scheduling problems with other control functions; (3) uncertainty; and (4) the absence of a relation between mathematical optimization and real productivity, which is achieved by experienced humans.

As illustrated by the last aspect mentioned by Buxey, researchers in the operations research community have now begun to realize that the human scheduler cannot be replaced and needs to be considered when developing scheduling techniques [10]. The survey of Halshall et al. [8] also showed that companies felt that scheduling systems should support, instead of replace, the human scheduler. The same issue is stressed by McKay et al. [11], who give a number of reasons why the theoretical approach from operations research does not work in practice. Schedulers have to handle a very large variety of elements which are prone to disturbances. Humans are able to use hard and soft information in scheduling; they use intuition to fill blank spots in the information. Furthermore, schedulers are able to influence some constraints of the shop floor, e.g. altering the short-term capacity.

Despite the problems and issues that have arisen in the last years and that have been discussed above, the recent survey of Halshall et al. [8] shows that the focus of scientific research in scheduling has not changed significantly. Halshall et al. [8] classify recent operations research and management science literature on production scheduling into three categories: theoretical papers, practical papers and mixed papers, i.e. theoretical, but based on a real-life framework, but without application. The period considered is 1986–1990. The results show that theoretical papers by far dominate the reported work, which is to be regarded as unfavourable, because there is a great need to report on and learn from successful and failed implementations of scheduling systems.

3. THE APPLICABILITY OF AI TECHNIQUES

Partly triggered by the limited success of operations research in improving industrial scheduling practice, and partly triggered by the emergence of artificial intelligence technology, some researchers and practitioners in production scheduling began to realize that to capture the scheduling problem, a new approach had to be used altogether. Artificial intelligence seemed to provide a better basis for modelling and solving the scheduling problem: artificial intelligence research had already achieved significant successes in solving complex problems in a number of scientific fields. In particular, artificial intelligence was expected to be capable of capturing the formerly intangible human decision behaviour in scheduling.

Grant [12] advocated the potential use of artificial intelligence in scheduling, by comparing operations research and artificial intelligence methods in the context of developing a scheduling system for repair job scheduling. Artificial intelligence techniques, by modelling human expertise, turned out to be useful to develop more efficient search strategies than would have been possible with operations research techniques. A prototype scheduler is developed, but the author does not indicate whether the system has been implemented or not.

The applicability of expert systems to job shop scheduling is also investigated by Randhawa and McDowell [13]. The problem of job shop scheduling is described from two perspectives: industry and academia. Industry has generally focused on pragmatic approaches to job shop scheduling, such as just-in-time (JIT), manufacturing resource planning (MRP), and optimized production technology (OPT). Academia has attempted to solve the job shop scheduling problem by mathematical approaches or to predict system performance by using simulation. Randhawa and McDowell state that these efforts from academia show that mathematical techniques are not suited for solving real-world problems. Because of the limited applicability of operations research techniques in job shop scheduling, the potential benefits of artificial intelligence techniques are discussed.

However, from other reports on the applicability of artificial intelligence in scheduling in
practice it can be concluded that the same problems that hampered implementation of scheduling techniques from operations research in practice also arise in the application of artificial intelligence to production scheduling. Kathwala and Allen [14] list a number of existing expert systems for scheduling and mention some issues that should be taken into account when developing expert systems for job shop scheduling. The problem solving domain should be well-understood, stable, and not subject to negotiation. Furthermore, human experts should be available and willing to co-operate; they could fear to lose their jobs and, therefore, obstruct expert systems development. Also, the costs of expert systems, which can become very high, should be carefully evaluated against the potential profits. Clearly, these issues are similar to those in operations research.

In [15], Kanet and Adelsberger discuss the applicability of expert systems to production scheduling. A state-of-the-art review is given, along with the remark that the area of expert systems in production scheduling is still in its infancy. They indicate that in order to encompass sole mimicking of human scheduling behaviour, successful scheduling systems of the future should be able to enumerate more alternatives than a human scheduler can, and be able to learn from experience. This leads to the observation that artificial intelligence not only inherited the problems of operations research, but that some additional pitfalls were introduced as well. This is illustrated in the work of Randhawa and McDowell [13], who indicate that a prerequisite for developing an expert system for production scheduling is the availability of expert knowledge. Unfortunately, this knowledge is dispersed among operators, foremen, supervisors, schedulers, etc. They envision that this problem may be tackled by simulating the job shop and training experts by this simulation. The resulting expert system then has to be evaluated and modified in the real job shop.

Another issue is discussed by Byrd and Hauser [16], who indicate that although expert system technology provides a means for organizations to achieve faster and more consistent decision making by removing human errors and inefficiencies, even highly automated systems need human beings for supervision, adjustment, maintenance, expansion and improvement. The introduction of expert systems may lead to cognitive starvation which endangers the essential human contribution to the scheduling process. In other words, if tasks are transferred from the human to the system, the human loses experience in his or her work. The risks of cognitive starvation have for example been experienced in the process industry [17]. If too many tasks are allocated to the system, the human does not have opportunities to build up a mental model of the system. As a result, exceptions which the system is not able to handle cannot be solved by the human either.

The problems of artificial intelligence techniques that have been discussed above hampered implementations of such systems. Kerr [18] describes a failed implementation of an expert system that was aimed at replacing the human scheduler. Even a simplified system that was developed after the initial failure was abandoned by the scheduler. Five reasons are given for the lack of success: (1) complexity of knowledge elicitation; (2) complexity of the relation between the human scheduler and the system; (3) uncertainty; (4) difficulties in human–computer interaction; (5) oversimplification of the problem. In a panel discussion report by Kempf et al. [19], implementation problems of artificial intelligence-based schedulers are discussed. They observe that there is a great disparity between the number of papers that have been published about artificial intelligence-based scheduling tools and the number of systems actually in use. A number of cases are discussed where attempts have been made to implement scheduling systems. Only one of these cases has been proven successful, and, moreover, it has been realised in a relatively simple manufacturing environment. Five main problems regarding implementations of artificial intelligence based scheduling systems are identified: (1) inadequate understanding of dominant domain characteristics, for example the existence of a bottleneck; (2) inappropriate reliance on locally greedy strategies, e.g. the use of priority rules do not guarantee good performance; (3) misuse of shallow expert knowledge, which is caused by the fact that experts tend to give inaccurate knowledge to the developers; (4) excess concern about trivialities, for example to label a schedule with one minute overlap as infeasible; (5) improper problem
segmentation, which happens when a part of the problem is inappropriately generalized to the whole problem. Other problems that are mentioned in the report are inadequate data availability and accuracy, and a negative disposition of personnel towards computers.

4. MANUAL SCHEDULING

Sanderson [20] summarizes and reviews 25 years of work done on the human role in scheduling. Two types of studies are discussed in the review: laboratory studies and field studies. Sanderson also discusses methodological and conceptual aspects of the literature reviewed. The laboratory studies summarized in Sanderson's review have mainly focused on three themes: comparing unaided humans with scheduling techniques, studying interactive systems of humans and techniques, and studying the effect of display types on scheduling performance. However, there are almost as many tasks studied as there are laboratory studies, and, therefore, generalizations from these studies are difficult to make. Moreover, the research questions, which mainly focus on comparisons of humans and techniques, are no longer relevant today. Field studies have mainly focused on highly experienced schedulers with very little decision support. Unfortunately, field studies in production scheduling have received little attention in the last decade.

Sanderson concludes with the observation that more and better co-ordinated research on the human factor in scheduling is required. The research reported in the review is widely dispersed over a variety of research journals and the reported works are often carried out in isolation from each other. She also notes that a common research question in much of the literature reviewed—which is better, humans or algorithms?—is no longer relevant. Humans and algorithms seem to have complementary strengths which could be combined. To be able to do this a sound understanding of the human scheduler is needed.

However, despite Sanderson's call, recent field studies on the human role in scheduling are scarce. An exception to this can be found in [21], where a research is described on the effectiveness of the hierarchical production planning (HPP) paradigm in dealing with uncertainty. A cognitive analysis was used to identify the decisions made in response to uncertainties in the manufacturing system. This resulted in an in-depth field study at a printed circuit board (PCB) factory. The human scheduler is especially important in managing uncertainty (see also [22]).

The field study in the PCB factory is also reported in [23]. In this paper, the formal vs the informal scheduling practices are compared in the context of managing uncertainty. Several interesting aspects of the scheduling practices are mentioned in this study. The scheduler worked with multiple schedules: a political schedule for the world to see, a realistic schedule, an idealistic schedule, and an optimistic schedule that was verbally communicated to the line. The scheduler did not take the current situation for granted, instead, he endeavoured to influence the amount and allocation of capacity, the amount of customer demand, the technical characteristics of machines (e.g. to minimize set-ups). The scheduler employed a large number of heuristics (more than a hundred) to anticipate possible problems and take precautionary measures.

In [24], the decision behaviours of four production schedulers in a truck manufacturing company are investigated by means of a quantitative model. This model consisted of three parts: performance variables, action variables and disturbance variables. The results show that schedulers who control equal production units show quite different decision behaviours. Also, a 'good' schedule turned out to be no guarantee of good performance. Moreover, some scheduling actions work positively in the short term but negatively in the longer term. However, the methodological discussion of the case made clear that it is very difficult to construct a reliable quantitative model of production scheduling.

5. USE OF TECHNIQUES BY HUMANS

The question why humans still prefer their heads instead of decision techniques, given the fact that cognition is bounded and that techniques can help humans to increase performance, is discussed by Kleinmuntz [25]. A common explanation is that people are unwilling to settle for techniques they know are imperfect and erroneously believe that increased mental effort will improve performance. The
question of how to improve decision rule use is studied by Davis and Kotteman [26]. They investigated the determinants of decision rule use in a production planning task. Decision rule use 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. However, measuring the performance of production scheduling has recently been recognized as a very complex problem [27]. Apart from basic criteria such as the absence of possibilities for trivial improvements and feasibility, no objective criteria can be set. Performance feedback can be given by monitoring performance over time, but this is of limited value when the manufacturing environment is unstable. Davis and Kotteman [26] indicate that a somewhat less effective measure to improve decision rule use is to explicitly describe the performance characteristics of a rule (i.e. the way a certain rule effects a certain performance) to humans, in this way making the rule more transparent. According to Norman [28], the transparency of a decision rule is especially important in situations where critical, novel or ill-specified problems have to be solved. In these cases, humans want to be in direct control, without the visible existence of a technique. This he refers to as “first-person” interaction. On the other hand, if the task that has to be performed is laborious or repetitive, the visible existence of a technique is preferable. In these cases, humans give commands to the (computerized) technique which then solves the problem. This is referred to by Norman as “third-person” interaction.

Apart from problems regarding the measurement of performance in production scheduling, there is another reason against offering performance feedback to human schedulers. While performance feedback has been found to improve decision rule use, it is also found to impair effective learning in complex tasks. Though feedback about the effectiveness of behavior has long been recognized as essential for learning in tasks, and, as found more recently, stimulating decision rule use, such feedback at least has to be specific and timely to be effective. In complex tasks where the relation between actions and outcome is unclear, offering feedback only about performance may be counterproductive. The reason for this is that outcome feedback might cue a focus on evaluating one’s competence rather than on increasing competence, which could result in a maladaptive behavior pattern [29]. Consequently, because action-effect relations in production systems are very hard to grasp, mental models of schedulers are prone to become inaccurate and variable. This is confirmed by Moray [30], who studied a supervisory task controlling a simulated discrete production system. The study of the individuals’ behavior shows that there is variability between individual operators in system intervention. Some operators decide to manually schedule parts of the system even when no faults are occurring at all, possibly to prevent faults from occurring, while others decide to leave the scheduling decisions to the system. To improve decision behavior in controlling complex systems, cognitive or learning-oriented feedback is required [29, 31-33].

6. USE OF DISPLAY TYPES BY HUMANS

Both in the operations research community and in the applied psychology community, research has been done on the effectiveness of various display types in scheduling tasks. In the operations research community, the GANTT chart is generally seen as an effective means to represent scheduling problems to humans. A well-known example of a type of information system where the GANTT chart is used to represent the scheduling problem is the electronic Leitstand [15, 34]. Besides an electronic GANTT chart, manipulation functions, evaluation functions, and automatic algorithms are offered in such systems. An example of such a system is given in [35], where a decision support system for production scheduling that combines algorithmic procedures and interactive manipulation is presented. The manual functions and the graphical representation of the production system give the user significant influence over the scheduling process. Moreover, automatic algorithms can be used to propose schedules to the user. The applicability of the system in practice looks promising according to various authors, although reports about implementations are difficult to find in the literature.

There are other studies on the effect of type of display on scheduling that show that graphical displays such as electronic GANTT charts do not guarantee better performance.
This was first demonstrated in an experiment by Sharit [36], who studied the effect of display type on scheduling performance. Kerr [18] describes how the failed implementation of an expert system was followed by an attempt to implement a much simpler system, based on an electronic GANTT chart. However, the simple system was also rejected by the scheduler in favour of the GANTT chart on the wall of the scheduler's office that was also used before the system was implemented. There was considerable reluctance on the part of the scheduler to move to an unfamiliar representation of the scheduling problem on a screen where only part of the schedule could be seen at once, and on which jobs could only be manipulated by mouse or keyboard.

In a study by Danek and Koubek [37], the effect of display type on performance in a scheduling task is studied in a laboratory experiment. Integral display facilities turned out to increase performance in scheduling tasks where integration of information is required, i.e. where the amount of task elements to be handled simultaneously is high. If the amount of task elements is relatively low and therefore focused attention is required from the human scheduler, integral information representation by means of information technology will be counterproductive, because in these cases the image has to be mentally decomposed to extract the necessary information.

7. DISCUSSION

In this paper we have given an overview of the applicability of techniques and the role of humans in production scheduling. The field studies on manual scheduling have shown that much expertise is used by humans to manage instability in the manufacturing process. A large amount of time of the scheduler is spent on identifying, communicating and negotiating about constraints. The literature about the applicability of operations research and artificial intelligence techniques gave various reasons for the shortcomings of these techniques in practice. When summarizing these problems, the following issues are found to be inadequately covered:

- robustness;
- dealing with complexity;
- performance measurement;
- organizational embedding;
- data availability and accuracy;
- interaction with human scheduler;
- learning from experience (artificial intelligence techniques);
- reliable human experts (artificial intelligence techniques).

Most authors agree that humans still play an essential role in the scheduling function. Therefore, techniques, usually incorporated in a computerized information system, have to interact with the user through a user interface. Various research has been conducted on the effectiveness of types of displays in production scheduling. The electronic Gantt chart is widely seen as an effective means to represent scheduling problems to humans. However, it has also been shown that this type of problem representation does not guarantee successful use of the system. Regarding the use of techniques by humans, performance feedback and transparency are found to be important conditions, although performance feedback is hard to give. Moreover, while performance feedback has been found to improve decision rule use, it is also found to impair effective learning.

The following issues regarding the use of techniques by humans remain unclear. Firstly, research on human scheduling and techniques has not led to much modelling effort to synthesize the insights of various fields to enable design of successful scheduling systems. Secondly, almost no field research has been conducted on why schedulers either use or circumvent systems. Thirdly, although the success of techniques is frequently found to depend on factors such as uncertainty and complexity, the importance of characteristics of production units on the success of scheduling techniques in practice is not clear. Fourthly, although the organizational embedding of scheduling systems is frequently mentioned to be an important factor in the success of scheduling techniques, almost no research on this problem has been carried out.

Some of these problems are caused by the fact that research on production scheduling is highly fragmented over various research communities, and publications are dispersed over journals on artificial intelligence, psychology, operational research, production control, decision science,
industrial engineering and so on. This problem was also recognized by Sanderson writing in 1989 [20], but the situation has not improved much since.

An attempt to tackle this problem can be found in [38], where a framework for decision support in production scheduling tasks is described. Various aspects of human decision behaviour are discussed in the context of the production scheduling task. A framework is given for decision support in several types of production systems. However, the framework needs more validation in practice in order to provide a sound basis for practitioners.

Most of the literature reports give little indication of whether the system has been implemented in manufacturing practice, and for those systems that have been implemented, what types of implementation problems were encountered. Most reports focus on the system's architecture and implementation issues are apparently regarded as trivial. The success of scheduling techniques in practice can only improve when researchers are aware of the implementation pitfalls through learning from each other’s experiences.

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ADDRESS FOR CORRESPONDENCE: VCS Wiers, Eindhoven University of Technology, Faculty of Technology Management, P.O. Box 513, Eindhoven NL-5000 MB, The Netherlands. e-mail: v.s.c.wiers@tm.tue.nl