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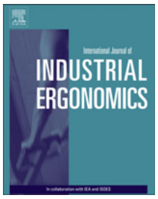

The nature of expertise in industrial scheduling: Strategic and tactical processes, constraint and object management

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ABSTRACT

This paper focuses on industrial scheduling expertise from a cognitive and ergonomic perspective. In line with the authors' previous study of timetabling, it considers both a higher level of abstraction in the cognitive control of symbolic processing during scheduling, defined by strategic processes, and a lower level, specified by tactical processes. Within the tactical level of control, two dual problem spaces can be defined: the Constraints Space (CS) and the Objects Space (OS). The constraints adopted in this paper are considered as relations between variables that cannot be represented in the solution (a Gantt chart). Objects, on the other hand, are constraint satisfactions and can be represented in the solution. This study compared twelve novices and six experts as they scheduled and then rescheduled manufacturing orders with the use of a Gantt chart. Actions on the interface and concurrent verbal reports were collected. As was the case for the scheduling of timetables, experts used a higher level of abstraction than novices in the control of processing. This was particularly evident for generic procedures, which are found less often in timetabling. Experts were more likely than novices to use external representations (objects) as activity support, whilst novices managed more constraints in their heads. Finally, in comparison with object management, constraint management is proportionally more important in timetabling than in industrial scheduling.

Relevance to industry: A better understanding of the processes used by schedulers would bring about improvements in human–machine cooperation for scheduling. This stake is crucial to the enhancement of productivity and customer satisfaction. Moreover, the task of schedulers is to design a schedule, rather than to execute it. One of their roles is to contribute to the prescription of work carried out on the shop floor. Since scheduling decisions impact on workers, it is also important to understand schedulers' problem-solving processes.

1. Introduction

Scheduling problems are commonly defined in terms of allocating tasks to resources over time (e.g., Baker, 1974; Crawford et al., 1999; Hoc et al., 2004; Jorna, 2006; Kiewiet et al., 2005; van Wezel et al., 2011). They can be found in a wide range of fields, including manufacturing systems (e.g., McKay et al., 1995), transportation planning (e.g., Gacias et al., 2010; van Wezel and Jorna, 2009), hospitals (e.g., Mietus, 1994; Sakphisal and Higgins, 2010), and university timetabling (Hoc et al., in press). The extent to which similarities and differences exist across such diverse domains is still open to question, both in terms of cognitive processes and expertise. In order to explore this issue, the same theoretical framework and method were used as in the authors' previous study of timetabling (Hoc et al., in press). By applying this framework to industrial scheduling, it was possible to focus more on representational aspects than on procedural aspects. Thus, it sheds light on new features of industrial scheduling, which, to date, have mainly been studied from a procedural viewpoint.

In industrial companies, planning and scheduling activities are imperative for the efficient management of production in a rising competitive environment where manufacturing costs must be reduced. Operations research has always been very active with regard to these issues. With the use of mathematical methods (algorithms, heuristics – e.g., Pinedo, 1994), however, it is

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becoming clear that such research serves more as a software supplier (e.g., APS: Advanced Planning and Scheduling) by automating the scheduling process, than as a designer of human operator support.

Until now, most research studies on scheduling expertise have dealt with observational field studies that frequently involve only one individual (Sanderson, 1989), and mainly take a procedural viewpoint. For instance, in the context of the printed circuit board industry, McKay et al. (1995) gave a very detailed description of the scheduling process of one individual, in terms of decision-making. Their aim was to encode human schedulers' heuristics (a set of decision rules) in a decision support system. Wiers (1996) used a field study approach in his attempt to model scheduling decisions in a truck manufacturing company. The objective of the study was to describe the inputs and outputs of the decision of the four schedulers rather than their cognitive processes, which the author called the "black-box". Many research studies carried out in a laboratory setting have also been handled from a procedural viewpoint. They compared human schedulers' performance with scheduling rules (Moray et al., 1991; Nakamura and Salvendy, 1988), using specific models to emphasize procedural knowledge implied within the realization of a task (e.g., GOMS-type model — Tabe and Salvendy, 1988; Tabe et al., 1990). Adopting the same procedural viewpoint, Sanderson (1991) tried to model scheduler activity using Rasmussen's decision ladder (Rasmussen, 1986). Her framework describes the different cognitive operations involved in a scheduling activity with a set of production rules (condition and action of each production activity).

The procedural aspects of goals management have also been studied from within the context of scheduling. For example, Tabe and Salvendy (1988) showed that schedulers could favor one goal at the expense of another, because of conflicting goals (tardiness vs. shop utilization). This result points to the weighting of goals and the rise of conflicts (Higgins, 1996; Mietus, 1994). For instance, a goal that aims to minimize tardiness may contradict another goal, such as the maximization of machine utilization.

Alongside the procedures and goals that are implied within scheduling, decision-making is a viewpoint that relates to the nature of the representations processed. However, the nature of these representations is relatively unknown. Kiewiet et al. (2005) conducted an empirical study within the context of the Netherlands Railways, to determine schedulers' cognitive maps (or mental models). The task of the participants was to use cards to produce graphs that represent their domain knowledge model for solving scheduling problems. The results showed a strong variability in terms of domain representation and knowledge.

This study of industrial scheduling, which takes the form of a Gantt chart, has adopted the same viewpoint of constraints and objects management used by its authors in a previous study of timetabling (Hoc et al., in press). A constraint can been defined as a relation between variables that cannot be represented in the solution (the timetable). Objects are constraint satisfactions that can be represented in the representational system that is required for the solution. In terms of this distinction, scheduling develops within two problem spaces: the Constraints Space (CS) and the Objects Space (OS). Operations on constraints (e.g., constraint formulation) and operations on objects (e.g., object modification) define a low level of abstraction in the symbolic control of processing, and are known here as tactical activities. The complementary procedural viewpoint from which goals (e.g., minimizing makespan) and procedures (e.g., Shortest Processing Time algorithm) are managed is described as a higher level of abstraction. Operations at this level (e.g., goal formulation, procedure formulation) are termed strategic activities. From a cognitive and ergonomic perspective, this paper aims to give some insights into expertise in scheduling. It takes an approach that examines scheduling deals from two complementary procedural and representational viewpoints. This paper's specificity is to stress the satisfaction of various and heterogeneous constraints, an important feature of scheduling problems in a single representational system required for the solution (a Gantt chart).

Although laboratory studies are a useful source of information on scheduling, Crawford et al. (1999) criticized this method because of the absence of complexity, uncertainty, and disturbance, some of the major components of real dynamic manufacturing environments. MacCarthy et al. (2001) and Jackson et al. (2004) added that theoretical scheduling research dissociates scheduling problems from the context in which they occur. Scheduling not only implies resource allocation decisions, but also communication within and without networks, the collection and distribution of information, and the anticipation of problems. This has been observed previously (Jackson et al., 2004; Stoop and Wiers, 1996).

Clearly, this paper takes an experimental approach to expertise that may well give rise to similar criticisms with regard to ecological validity. For these authors, field study remains the most valid approach to understand scheduling practice. Such an experimental approach should be considered as complementary to this kind of study, but with a controlled ecological validity. First, participants were given any general information they may need in a real context. Second, all expert participants had a non-negligible experience of planning and scheduling. Third, a method was developed to specifically study the cognitive aspects of industrial scheduling. Such a method is time-consuming to apply in real settings, because scheduling and other related activities (e.g., information gathering or negotiation with departments of the company) are spatially and temporally distributed. Thus, it was necessary to optimize the complexity of the task.

The main theoretical foundations of this experiment are developed in Sections 2 and 3 of this paper. First, two levels of abstraction in the cognitive control of processing involved in scheduling are considered. These levels are defined in terms of strategic and tactical activities. Within the tactical level, a distinction is made between constraints and objects for describing scheduling activity, notably using the concept of Representation and Processing Systems (Hoc, 1988), which is similar to the notion of mental models or points of view. Section 4 also underlines the properties of expert behavior that are relevant to the interpretation of the results of this study. Section 5 comprises a formulation of the main hypotheses derived from the theoretical framework. Section 6 describes the experimental task, the participants, and the data-gathering and data-coding methods used. Section 7 then presents the main results of the study. Finally, the results and prospects for scheduling expertise and for interface design are presented.

2. Levels of cognitive control in planning and scheduling

From a psychological perspective, scheduling as a cognitive activity implies planning mechanisms. Although a plan is often understood in the limited sense of an action plan, it can be more generally considered as an abstract representation that is capable of guiding activity during scheduling (Hoc, 1988). Thus, in the present experiment, verbal reports of plans will be taken as cues of strategic activities. Moreover, planning develops within abstract spaces and implies different levels of cognitive control. By studying changes of representation during reasoning and problem solving in an industrial systems context, Rasmussen (1986) defined two orthogonal dimensions in abstraction. The first one, a whole-parts hierarchy, is used to describe the decomposition of a plan into its parts (details are abstracted from a lower space to a higher one). The second dimension is the abstraction hierarchy (a means-ends hierarchy), which is considered useful for describing different levels of control of the cognitive processes in solving a scheduling problem. This hierarchy defines a functional decomposition whereby a system exists at different levels of abstraction using how and why relationships.

Rasmussen's levels of abstraction have already been suggested as a useful way to study scheduling by MacCarthy et al. (2001). From the viewpoint of the present study, the highest level of abstraction concerns goals and procedures managed by the scheduler, whereas the lowest level of abstraction deals with their realization. In Section 3, the implementation of goals and procedures are described in terms of constraints and objects management. To differentiate between the highest and lowest levels of abstraction in the control of processing, the following terminology has been adopted. Strategic activities are those with a high level of abstraction in the control of processing; for example, goal formulation or procedure formulation. Tactical activities are those activities that have a low level of abstraction in the control of processing; for example, operations of constraint formulation or object modification.

3. Coordinating multiple RPS in an external RPS: constraint and object management

One important aspect of the scheduling process is the management of the constraints of a problem. McKay et al. (1988) used surveys and case studies to produce a list of two hundred kinds of constraint that could be more or less important for schedulers. These constraints can vary from the due date of a manufacturing order, to the mood of the workers, or the climate. Moreover, 80–90% of human schedulers' time is spent in identifying problem constraints rather than in dispatching (Sanderson, 1989). From these reports, it is reasonable to assume that schedulers represent a particular scheduling problem as a set of constraints that need to be satisfied, some of which can be contradictory. The identification of constraint management is at the core of the present experiment.

In existing literature on scheduling, a constraint is seen as a rule that restricts the solution of a problem (van Wezel and Jorna, 2006). From a cognitive viewpoint, the set of constraints to be satisfied can be considered in terms of the Representation and Processing System (RPS), a notion introduced by Hoc (1988) in the context of design problem solving. According to this author, a design problem is a task that is represented by the problem solver as the search for a detailed representation of the goal through shifts in representation format during problem solving. Thus, scheduling can be considered as a particular case of design problem solving, which "at some very abstract level, is the process of transforming one set of representations (the design brief) into another set of representations (the contract document)" (Goel, 1995, p. 128). One difficulty for resolving design problems is that constraints belonging to the design brief can be expressed in various formats within the specifications, whereas the solution must be expressed in a single external representation system with a particular format. For instance, in architectural design, specifications of functional features, cost of materials, topologic constraints, metric constraints, and so on, are expressed in various formats and must be coordinated in a three-dimensional representation of a building (Lebahar, 1983).

Schedulers in manufacturing systems must take into account a number of constraints during the task of allocating job operations to machines and periods of time. Moreover their aim is to meet performance criteria, such as the maximization of productivity or the minimization of lateness. From the perspective of an experimental approach, in this study it was necessary to restrict the complexity of the industrial scheduling task to the following constraints: processing time, due date and periods of maintenance. This multiplicity of information formats can be defined in terms of multiple and various RPS (representations linked to processing in RPS), which must be expressed in an external RPS with a particular format: in this study, we used a Gantt chart.

Different Gantt chart formats exist. This study adopted the Gantt chart most often used in manufacturing systems. This Gantt chart is based on machines (on ordinate) and time (on abscissa). Job operations (i.e. manufacturing orders) are represented by bars that are proportional in length to the processing time required and are differently colored for each job. On this external RPS, some constraints are visible and others remain hidden. For example, on the Gantt chart in Fig. 1, we can see that manufacturing order 1 can be delivered at time *t*, but the due date could be $t + 1$; the due date constraint is not directly expressed in this Gantt chart. On the contrary, precedence constraint is visible in the solution: the cutting operation takes place before the welding operation and before the painting operation. Operation duration is a constraint expressed in the solution by means of the length of the segment, which is proportional to the duration. Thus, this Gantt chart format allows machine utilization to be made more visible, and favors quality of performance and reported goals.

This distinction between visible and hidden constraints helps to define two types of representation: constraint and object. According to Stefik (1981), a constraint is a relation between variables, and describes an object partially. Until now there has been no clear-cut distinction between the two entities. In the present study, a constraint is defined in the strictest sense, as a relation between variables that cannot be represented in the solution (Gantt chart). On the other hand, objects are constraint satisfactions and can be represented in the representational system required for the solution. As a result, the Gantt chart expresses objects, that is to say visible constraints (each segment in the Gantt chart – Fig. 1). However, it cannot express hidden constraints (e.g., due date constraint). From this distinction, it is possible to describe operations on constraints and operations on objects. It was assumed that two dual spaces would be involved during scheduling: the Constraints Space (CS) and the Objects Space (OS). Operations within and between these spaces define a low level of abstraction in the control of processing – namely

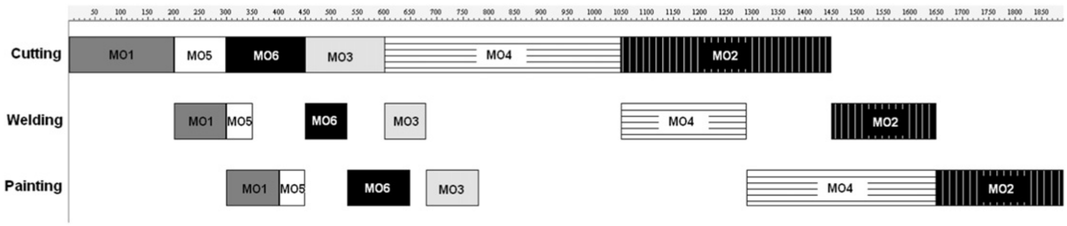

Fig. 1. Example of a Gantt chart designed on Lekin®. 6 Manufacturing Orders (MO) are scheduled. The due date constraint is not directly expressed in the Gantt chart whereas operation durations are constraints expressed in the solution (objects).

tactical activities. As opposed to this tactical level, the highest level of abstraction in the control of processing corresponds to the verbal reference to procedures and goals management, as strategic activities. Thus, scheduling will be described for both strategic and tactical activities, and, within the tactical level, for operations within and between the CS and the OS.

4. The scheduling expertise

Although cognitive psychology literature cannot provide a consensual definition of expertise (Cellier et al., 1997), it is often described as a state reached after a long experience in a particular domain (Ericsson and Smith, 1991). The study of expertise in scheduling is quite difficult because of a scarcity of expert operators and because the precise definition of a scheduler is not consensual (Crawford et al., 1999). For this reason, planning and scheduling can be seen as a continuum of activities and roles (MacCarthy et al., 2001). On the shop floor, between 10% and 20% of schedulers' time is spent in scheduling; the rest is spent determining relevant information that might affect the current schedule (Fox, 1990). For that reason, schedulers are, in the main, production managers. Moreover, students are trained in production management in general rather than in scheduling in particular. After leaving school, most of them become production managers. Therefore, a comparison of experts and novices in production management, as carried out in the present study, is a relevant approach.

From among the general characteristics of expertise, those that are relevant to scheduling activity and for the interpretation of the results of this study will be selected. Cellier et al. (1997) showed that experts have more planning ability than novices for two reasons. First, experts have a great ability for anticipation. Second, experts are able to access a more global and functional (abstract) representation of the system. Consequently, they have better abstraction abilities. By using a top-down planning strategy, experts can progressively refine an abstract plan that is formulated in terms of goals (Hoc, 1988). Within the scheduling domain, one of the goals managed by experts is the introduction of a margin into a schedule in order to anticipate disruptions and to facilitate rescheduling (McKay et al., 1995). Other goals are related to the ability to maximize the utilization of resources and minimize the average lateness of orders (McKay et al., 1992).

Another general feature of expertise is that the structure of knowledge differs among experts and novices (Glaser and Chi, 1988). Such a difference can lead to different types of problem-solving guidance. Novices are guided on the sole basis of surface features of the problem. By contrast, experts spend quite a long time in identifying the deeper principle of the problem; thus, they are guided on the basis of a problem's deeper features (Larkin and Reif, 1979). This difference in terms of problem-solving guidance is also related to the definition of meaningful cues in a particular environment. Although experts are able to control their activity on the basis of internal representations, they are also able to extend their cognition toward their environment, defining meaningful cues within it that are capable of guiding their cognitive processes (Hoc and Amalberti, 2007). The main reason for this extension of cognition is the management of mental workload within acceptable limits. In the present study, one could assume that experts do not need to make explicit the deeper structure of the constraints (a relation between variables) satisfied by objects (surface features of constraints). To a certain extent, experts can manipulate objects directly without processing the constraints they satisfy. More precisely, this in-depth approach to scheduling problems can be seen as an encapsulated knowledge, which can be extended, if necessary (e.g., Boshuizen and Schmidt, 1992; in medical domain).

Finally Glaser and Chi (1988) stated that the content of knowledge is also determined by expertise, because experts possess greater domain knowledge than novices. Scheduling activity is also influenced by this characteristic, because schedulers can change the specifications of a scheduling problem by, for instance, modifying constraints or objectives (McKay et al., 1992). In some contexts (e.g., time pressure), experts can violate or relax some constraints (Higgins, 1996) to create an alternative schedule that is related to a performance quality criterion prescribed by the company (McKay et al., 1995).

5. Hypotheses

Two main hypotheses can be put forward, based on discussions of previous theoretical and experimental results.

(H1) The first hypothesis is in accordance with the work carried out by Cellier et al. (1997) and the authors' previous study of timetabling. It states that, in relation to abstraction abilities, experts may use a more abstract and functional representation of the scheduling problem than novices. Two sub-hypotheses can be derived from this abstraction ability.

  (H1.1) The control of processing during scheduling would be on a strategic level, and planning guidance would be used by experts in a top-down way, progressively refining an abstract plan that is formulated in terms of goals (Hoc, 1988). A first specific goal pursued by experts could be the introduction of a margin into their Gantt chart (McKay et al., 1995). A second goal could be to minimize waiting time in order to maximize resource utilization (McKay et al., 1992).

  (H1.2) In order to find a new solution, an expert could change the specifications of a scheduling problem by violating or relaxing some constraints (Higgins, 1996; McKay et al., 1992). In this way, experts can avoid looking at the problem from too narrow a viewpoint, and can set it at a higher abstraction level.

(H2) Second, in line with Hoc and Amalberti (2007) and the authors' previous study, it was expected that the required external representation format would be used more widely by experts than by novices. On a Gantt chart, objects could play the role of affordances and suggest manipulations. As a result, experts may be able to perform more operations on objects, as guidance representation, than novices. Such a result could be of interest for defining computer interfaces that are capable of supporting the scheduling activity.

6. Method

6.1. Participants

The twelve novices were students in production management, recruited from the University of Nantes (IUT: Polytechnic Institute). These students had a theoretical knowledge of scheduling methods, concepts, and rules and were familiar with the Gantt chart. Despite difficulties in finding available experts, six volunteers participated in the experiment. They were former students of the polytechnic institute, who had global experience in production management and scheduling, and were also familiar with the Gantt chart tool. All experts had worked for French companies for at least five years (mean: 9 years; standard deviation: 4.7 years); these companies were all involved in various types of manufacturing processes (e.g., aircraft manufacturer, automobile manufacturer, ship manufacturer, electronic components manufacturer, furniture company).

6.2. Experimental task

In order to optimize complexity, which should be neither too difficult for novices, nor too easy for experts, the participants were set a problem that was taken from a textbook case. The experimental task was divided into two stages. The aim of the first stage was to schedule six Manufacturing Orders (MO) for bicycles using three consecutive machines (cutting, welding, and painting) in a flow shop. Each participant was given an instruction sheet that showed the MO and their constraints: processing time, and due date (Table 1).

The participants had to achieve two classic/frequent goals in production management: maximize productivity, and minimize the number of late jobs. Participants were asked to continue working until they felt satisfied that they had achieved a solution that met both criteria. Moreover, they were aware of the likelihood of disturbances: “Lately we observed disturbances on machines of the shop. We called a company of troubleshooters to control the machines, but we don’t know when and how many times the company will proceed”.

Each participant had to use Lekin® (Feldman and Pinedo, 2001) to schedule the six MO (Fig. 1): Lekin® is a scheduling system developed at the Stern School of Business, NYU. It is an educational tool with the main purpose of introducing the students to scheduling theory and its applications. With this system, the user may modify a chart by moving the MO on the screen. However, MO moves that violate operation precedence constraint are barred.

There were several reasons for choosing this tool. First of all, despite the existence of such manufacturing scheduling software as Preactor or Ortems, no “standard” scheduling software currently exists. In industry, some companies use ERP (Enterprise Resource Planning), production management software that has scheduling functions, whilst others use Excel® to schedule production (as is the case for the aircraft manufacturer Airbus). Although Lekin® offers priority rules and optimization algorithms, it was decided in this experiment to opt for the ease of the manual mode. Students learned how to use this during an initial training stage. Each participant had as much time as was needed to make his or her final schedule. When the participant was satisfied with his/her solution, a second stage of the experiment was conducted. Information about period and duration of maintenance was given and the participant was invited to reschedule in order to consider this information (Table 2). The same goals (maximizing productivity and minimizing the number of late jobs) had to be achieved.

One difficulty encountered with this task was the participants’ inability to satisfy all constraints simultaneously, especially in terms of due dates and periods of maintenance. Finally, for each of the two stages of the task, participants could record their scheduling (or rescheduling) solutions by pressing a save button in Lekin®. This functionality gave participants the opportunity to compare several solutions during scheduling.

In order to evaluate performance quality, two viewpoints were adopted in this study. From a behavioral viewpoint, performance quality was assessed in terms of completion time and in terms of number of schedules recorded during each stage (scheduling and rescheduling) of the task. It was assumed that the latter criterion could point out a cognitive cost. From an industrial viewpoint, performance quality was assessed in terms of makespan (the total duration of the schedule), number of late manufacturing orders, and total lateness.

Table 1
Manufacturing orders (MO) and constraints of the scheduling stage.

MO	Goods	Processing time			Due date
		Cutting	Welding	Painting	
1	10 Blue bicycles for men	200 min	100 min	100 min	400 min
2	20 Red bicycles for men	400 min	200 min	240 min	1800 min
3	10 Blue bicycles for women	150 min	80 min	100 min	1500 min
4	30 Red bicycles for women	450 min	240 min	360 min	2050 min
5	5 Blue bicycles for men	100 min	50 min	50 min	1850 min
6	10 Red bicycles for women	150 min	80 min	120 min	1500 min

Table 2
Constraints of maintenance (periods and duration) for the rescheduling stage.

Machine	Period	Duration
Cutting	1400–1600 min	200 min
Welding	600–800 min 900–1100 min 1600–1700 min	200 min 200 min 100 min
Painting	No maintenance	

6.3. Data collection, coding method and coding scheme

Verbal “thinking aloud” reports and obvious actions were recorded on the Gantt chart at the same time as participants performed their scheduling task. A “thinking aloud” instruction was given in accordance with the work of Ericsson and Simon (1980). This method is particularly suitable for studying symbolic data that is processed in the working memory, and, in this type of symbolic task, does not affect operators’ performance. A protocol analysis was carried out using an encoding method, together with a predicate-argument structure supported by MacSHAPA software (Sanderson et al., 1994). The following coding scheme consists of two main classes of activities, which describe two levels of abstraction in the control of processing during scheduling activity. Strategic activities relate to procedure and goal management, and constraint violation. Tactical activities involve a set of operations, which are represented by arrows within the Constraints Space (CS), within the Objects Space (OS), and between the two spaces, or from the specifications (or designer’s preferences) to the CS (Fig. 2).

In the following sub-sections, a definition is put forward for each predicate. The Appendix includes argument definitions and examples extracted from the protocols for each predicate; these illustrate the encoding method.

6.3.1. Strategic activities

From a high level of abstraction in the control of processing, strategic activities organize a set of actions during scheduling problem solving. They relate to procedure formulation, goal formulation or evaluation, and constraint violation.

Procedure Formulation (PR-FORM) is related to a high level of activity. In this study a procedure could be a scheduling rule (or priority rule): for example, EDD (Earliest Due Date – First select operation on the job with the earliest due date), SPT (Shortest Processing Time – First select operation on the job with the shortest processing time), or LPT (Longest Processing Time – First select operation on the job with the longest processing time). A procedure could also be related to a particular application domain. For instance, operations with white paint could be chosen before those in a dark color.

Goal Formulation (GOAL-FORM). A goal directs an operator’s activity. In this study, the goals formulated were: minimizing makespan, minimizing job lateness, minimizing waiting time (the time a job must wait before being processed), and introducing margin (between manufacturing orders) to anticipate maintenance.

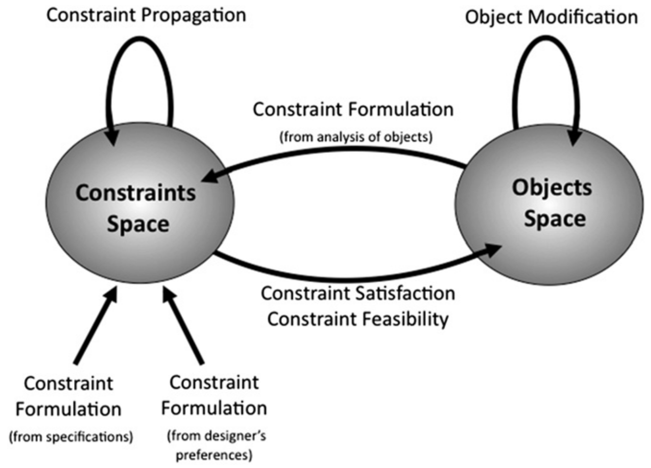

Fig. 2. Operations within and between constraints space and objects space (tactical level of control), after Hoc et al. (in press).

Goal Evaluation (GOAL-EV) involves evaluating (positively or negatively) a result after an action of moving a Manufacturing Order on the Gantt chart. The evaluation criterion is a property of the schedule (e.g., waiting time between operations), or a performance quality indicator (e.g., total lateness).

Constraint Violation (CTR-VIOL) is an elimination of constraint. This is not a mistake but a deliberate decision made by the scheduler. Constraint violation is a strategic activity because it implies the redefinition of the scheduling task. In this experimental study, schedulers could not negotiate; however, negotiation is possible on the shop floor. Furthermore, the satisfaction of some constraints could imply an important cognitive cost. Experts in scheduling may, therefore, decide to violate some constraints.

6.3.2. Tactical activities

Although they belong to a low level of abstraction in the control of processing, these symbolic problem-solving activities imply attentional resources and are far from automatized. They concern constraint formulation, propagation, feasibility, satisfaction, and object modification. These tactical operations can be described within two dual spaces: the Constraints Space (CS) and the Objects Space (OS). In general, operations on constraints were more commonly reported than operations on objects, which were more visible. The latter were coded on the basis of actions on the interface without verbal reports.

6.3.2.1. Transition operations from the specifications or designer's preference to the CS. Constraint Formulation (CTR-FORM) is the introduction of a new constraint in the scheduling process, which is not generated from the propagation of existing constraints. The predicate CTR-FORM codes a relation between the three variables: Order, Operation-machine, and Period. Each constraint formulation was qualified from the viewpoint of the origin of the constraint, that is to say its mode of introduction into the scheduling process: a) prescribed (specifications that can be identified before scheduling and cannot be ignored, including validity constraints); b) deduced (stemming from an analysis of the state of the solution, i.e., from the objects already defined); and c) introduced (stemming from the scheduler's knowledge or preferences).

6.3.2.2. Operations within the CS. Constraint Propagation (CTR-PRG) is the creation of a new constraint from already expressed constraints. This operation combines a set of previous constraints.

6.3.2.3. Transition operations from the CS to the OS. Constraint Feasibility (CTR-FEAS) is the consideration of whether an object is available for constraint satisfaction. Constraint feasibility activity ends when the test is completed; that is to say, when the scheduler has answered the question (either with a verbal report or an action).

Constraint Satisfaction (CTR-SATF) is the association of acceptable values with variables in order to make an efficient combination in the scheduling process. The scheduler shifts from CS to OS in order to define an object capable of satisfying the constraint. We code a satisfaction when an object is modified only in relation to a previous constraint management (e.g., formulation and propagation).

6.3.2.4. Operations within the OS. Unlike operations on constraints, operations on objects can be viewed on the Gantt chart and are not linked to verbal reports of constraints.

Object Modification (OBJ-MOD) is where one value of an object is modified.

6.3.2.5. Transition operations from the OS to the CS. The same CTR-FORM predicate, described in Section 6.3.2.1, is used. The value "deduced" from the "origin" argument enables the identification of this particular transition, which results from the analysis of objects on the Gantt chart (e.g., free time).

6.4. Statistical methods

Two main methods were used for the statistical analysis of the data. First, a Principal Components Analysis (PCA), a well-known variant of factorial analysis (Jambu, 1991), was performed with the support of Statistica© (version 6). Second, a Bayesian statistical inference was used (fiducial inference: Lecoutre and Poitevineau, 2005; Rouanet, 1996) to draw conclusions in terms of population effect sizes (δ) or calibrated effect size (δ/σ: the ratio between the population effect and the appropriate indicator of the individual differences for the effect). As such, it goes beyond a conclusion drawn solely on non-null effects. On the basis of a maximal a priori uncertainty, this method is complementary to the traditional Null Hypothesis Significance Testing, enabling a probabilistic judgment to be made on the population effect size. It serves to extend the Bayesian interpretation of the confidence interval so that, on completion of the experiment, it is possible to consider the range of values for the parameter with an acceptable guarantee (e.g., $\delta > a$, "a" considered as notable or $|\delta| < \varepsilon$, "ε" being negligible). In the results section, statements on population effect correspond to a probability of .90. When no relevant conclusion could be reached, at least with this guarantee, this was noted as "no gen.", meaning that no generalization in terms of population effect size could be reached.

7. Results

First, the PCA results for the scheduling and the rescheduling stage are presented. By discriminating between some strategic operations (such as goal formulation and evaluation for the scheduling stage, and constraint violation for the rescheduling stage), it was possible to identify two levels of abstraction in the cognitive control of processing. All strategic operations (including procedure formulation, goal formulation and evaluation, constraint violation) and all tactical operations (such as constraint formulation, and propagation) are then compared. The types of goal formulated during scheduling activity are reported. Distinctions between operations within Constraints Space, operations within the Objects Space, and transitions between predicates are then outlined. Finally, the descriptive differences between groups with regard to the performance quality of the participants are presented.

7.1. *Level of control*

PCA places emphasis on the first axes, with the same interpretation for both the scheduling and rescheduling stages. These first axes denominate the level of control. With regard to the former stage, the first axis is bipolar (explaining 41% of the variance), and contrasts two classes of activities (cumulated contribution of 86% to the first axis): tactical operations of constraint management (constraint formulation, propagation and satisfaction) vs. strategic operations (goal formulation and evaluation), to which expertise is correlated. As stated previously, these two classes of activity are interpreted in terms of levels of abstraction in the control of processing. Tactical operations define a low level of abstraction, whereas strategic operations involve a high level of abstraction. With regard to the rescheduling stage, the first axis is also bipolar (accounting for 32% of the variance), and contrasts two classes of activities (cumulated contribution of 69% to the first factor): tactical operations (low level of control) of constraint management (constraint formulation, propagation and satisfaction), vs. strategic operations (high level of control: constraint violation, goal formulation and evaluation) to which expertise is correlated. In this study, constraint violation appeared only during the rescheduling stage, and was related to constraints about periods of maintenance. A Bayesian statistical inference was carried out on the new variable (level of control) resulting from the PCA axes (Table 3).

Since the unit is arbitrary, the population effect size was assessed in relation to individual differences; thus, the effect was calibrated. For both stages, it can be concluded that there was a notable effect. In a comparison of novices and experts, experts used the strategic level for both the scheduling and rescheduling stages more frequently.

7.2. *Strategic operations vs. tactical operations*

Table 4 shows that, regardless of the level of expertise and stage of the task, tactical operations are carried out much more frequently than strategic operations (72.5% vs. 27.5%). This difference is greater for the rescheduling stage (84.2% vs. 15.8%) than for the scheduling one (60.9% vs. 39.1%). Moreover, whatever the stage of the task, the percentage of strategic operations for experts is much higher than for novices (32.4% vs. 22.7%). We cannot conclude a significant difference for the scheduling phase. However, for the rescheduling stage, the difference is significant ($d = 21.0 - 10.7 = 10.3\%$; $t(16) = 5.23$, $p < .001$), and Bayesian inference proves that it is notable ($\delta > 7.7\%$). This result is consistent with the analysis of the first axis following the PCA.

7.3. *Types of goal formulated*

Table 5 shows that, during the scheduling stage, novices formulated the goal of "minimizing makespan" (the total duration of the schedule) more frequently than experts ($d = 49.0 - 19.4 = 29.6\%$; $t(16) = 2.72$, $p < .02$; $\delta > 15.1\%$). On the contrary, experts formulated the goal of "minimizing waiting time" more frequently than novices ($d = 46.8 - 14.5 = 32.3\%$; $t(16) = 3.34$, $p < .005$; $\delta > 19.4\%$). It was assumed that the goal of "minimizing waiting time" corresponded to minimizing machine idle time, which is equivalent to maximizing machine utilization. These goals deal with periods of non-productivity. Goals formulated during rescheduling were not considered because of their very low frequency.

7.4. *Operations implying the constraint space (CS) vs. operations within the objects space (OS)*

During the scheduling stage (top of Fig. 3), novices produced, on average, 62 operations that imply constraints or objects, whereas experts produced 51 operations. Moreover, whatever the group, object modification represents about 50% of the operations at this stage. Operations within the OS occur much more frequently for experts than for novices ($d = 61.4 - 41.4 = 20.0\%$; $t(16) = 2.11$, $p < .051$; $\delta > 7.3\%$). Conversely, the percentage of operations implying constraints is much higher for novices than for experts, especially Constraint formulation from preferences ($d = 3.9 - 0.2 = 3.7\%$; $t(16) = 3.61$, $p < .003$; $\delta > 2.3\%$); Constraint propagation ($d = 10.1 - 5.0 = 5.1\%$; $t(16) = 2.25$, $p < .04$; $\delta > 2.1\%$); Constraint satisfaction ($d = 15.8 - 4.1 = 11.7\%$; $t(16) = 2.73$, $p < .02$; $\delta > 6.0\%$).

During the rescheduling stage (bottom of Fig. 3), novices produced, on average, 74 operations that imply constraints or objects, whereas experts produced 38 operations. Moreover, whatever the group, constraint formulation from specifications represents about 38% of the operations at this stage. This operation occurs much more frequently for experts than for novices ($d = 41.0 - 34.9 = 6.1\%$; $t(16) = 2.12$, $p < .051$; $\delta > 2.3\%$). Other operations imply constraints that are much more frequent for novices than for experts, especially Constraint formulation from preferences ($d = 1.9 - 0.0 = 1.9\%$; $t(16) = 2.30$, $p < .04$; $\delta > 0.8\%$); Constraint propagation ($d = 5.7 - 1.3 = 4.4\%$; $t(16) = 2.89$, $p < .02$; $\delta > 2.4\%$).

7.5. *Analysis of direct transitions from a constraint formulation*

This analysis of predicates covers transitions between tactical operations and strategic ones for both the scheduling and rescheduling stages. An analysis of the 1st order transitions from the predicate CTR-FORM to other predicates (20 for novices, 13 for experts for the scheduling stage, and 32 for novices, 18 for experts for the rescheduling stage) was carried out in order to gain more insight into the strategies. In particular, a comparison was made between the percentages of direct transitions toward tactical operations of constraints management and toward strategic operations. For the scheduling stage, experts show more frequent transition to strategic activities than novices ($d = 23.6 - 7.3 = 16.3\%$; $t(16) = 2.91$, $p < .02$; $\delta > 8.8\%$) and novices show more frequent transition to tactical activities implying constraints than experts ($d = 73.6 - 51.3 = 22.3\%$; $t(16) = 2.13$, $p < .05$; $\delta > 8.3\%$). The same results were obtained for the rescheduling stage: experts show more frequent transition to strategic activities than novices ($d = 14.9 - 3.5 = 11.4\%$; $t(16) = 4.16$, $p < .001$; $\delta > 7.7\%$) and novices show more frequent transition to tactical activities implying

Table 3

Comparison of novices and experts on level of control (first axis) used for scheduling and rescheduling. A positive value means a high level of control and a negative value means a low level of control.

	Novices		Experts		Calibrated effect (d/s)	t Test ($\alpha = 0.05$)	Calibrated effect size (δ/σ)
	Mean	Standard deviation	Mean	Standard deviation			
Level of control (scheduling)	−0.73	1.83	1.46	1.10	−1.34	$t(16) = -2.68$; $p < 0.02$; S	$P(\lvert\delta/\sigma\rvert < -0.61) = .90$; notable
Level of control (rescheduling)	−0.83	1.36	1.67	1.65	−1.72	$t(16) = -3.43$; $p < 0.004$; S	$P(\lvert\delta/\sigma\rvert < -0.94) = .90$; notable

Table 4

Percentage of strategic operations and tactical operations during scheduling and rescheduling stages ($\overline{N}$ is the mean frequency).

	Novices		Experts	
	Mean	Standard deviation	Mean	Standard deviation
Strategic operations (scheduling)	34.6	11.8	43.7	20.9
Tactical operations (scheduling)	65.4	11.8	56.3	20.9
Total	100.0 ($\overline{N}$ = 89.7)		100.0 ($\overline{N}$ = 89.5)	
Strategic operations (rescheduling)	10.7	3.6	21.0	4.7
Tactical operations (rescheduling)	89.3	3.6	79.0	4.7
Total	100.0 ($\overline{N}$ = 82.9)		100.0 ($\overline{N}$ = 47.3)	

constraints than experts ($d = 89.4 - 76.3 = 13.1\%$; $t(16) = 3.33$, $p < .005$; $\delta > 7.8\%$). This is consistent with novices greater tendency to work with constraints compared with experts, and with experts' higher level of control (strategic activities).

7.6. Performance quality

For the scheduling and rescheduling stages, performance quality was assessed from a behavioral viewpoint (completion time, number of schedules recorded), and from an industrial viewpoint (makespan, number of late manufacturing order, total lateness). For the scheduling step, the criterion of "difference in completion time" is marginally significant. The difference, which is a greater completion time for experts than for novices, is not negligible ($d = 22.0 - 15.0 = 7.0$ min; $t(16) = 1.67$, $p > .11$; $\delta > 1.3$ min). For the rescheduling stage, the "industrial" performance quality tends to be better for experts (less lateness is better than more lateness). The criterion "number of manufacturing orders in late" is better for experts but marginally significant and the difference is not negligible ($d = 1.2 - 0.5 = 0.7$; $t(16) = 1.76$, $p > .09$; $\delta > 0.2$). Finally, the criterion "total lateness" is better for experts but marginally significant and the difference is notable ($d = 365.8 - 50.3 = 315.5$ min; $t(16) = 1.77$, $p > .09$; $\delta > 77.1$ min).

8. Discussion

Before discussing the results of this study, a summary of the main findings about the significant and notable differences (inferential analyses) between experts and novices (Table 6) is presented.

This study identified two major results relating to expertise in scheduling: the high level of control with the use of strategic activities (our first hypothesis H1), and the external control of cognition with the use of the Objects Space (H2). These differences provide some insights into the nature of expertise in industrial scheduling.

PCA showed that experts adopted a more strategic level of control than novices during the scheduling and rescheduling stages (H1). This was especially the case for goal formulation and the evaluation of so-called strategic activities (H1.1). This finding confirms a higher abstraction ability in terms of a more abstract and functional representation of the scheduling problem for experts than for novices (Cellier et al., 1997; Rasmussen, 1986). Guidance at this strategic level of planning relates to goals refined by experts (Hoc, 1988), particularly the minimization of waiting time, with the probable aim of maximizing machine utilization (McKay et al., 1992). On the contrary, novices tried to minimize the makespan (total duration of the schedule). Actually, the two measures, "sum of waiting times" and "makespan", are both related to the productivity of the resources and should be considered together. In the present study, however, the software used for our experiments (Lekin®) explicitly presents two different measures: the makespan and the sum of waiting times. As shown in Table 5, to maximize the productivity, experts try more frequently to minimize the waiting times while novices prefer to minimize the makespan. This difference can be explained by the fact that novices, who in this case are students in production management, have been trained to use the makespan in order to maximize the productivity. On the other hand, experts prefer to minimize idle times they can observe directly on the Gantt chart, and, therefore, they focus on waiting times. In this study, therefore, experts favored the minimization of workers' free time over faster production. On the other hand, the goal of introducing a margin into the Gantt chart was not observed. McKay et al. (1995) pointed out that pursuing this goal was useful for anticipating disturbances and to facilitate rescheduling. The reason for this is possibly our choice of disturbances (uncertain duration and periods of maintenance). In future research work, other sorts of disturbance could be used, including the arrival of urgent orders, order cancellations, and stock supply issues (Davenport and Beck, 2000; Hoc et al., 2004; McKay et al., 1995; Sanderson, 1989). Moreover, two other results confirmed that experts used a higher level of control. In the rescheduling stage, experts formulated more strategic operations than novices; these were mixed in nature. The analysis of direct transitions from a constraint formulation also showed that experts were more able than novices to use strategic activities.

Besides goal formulation and evaluation, the strategic level of control appearing from the PCA for the rescheduling stage involves constraint violation (H1.2). Eliminating a constraint is a strategic operation because it implies the redefinition of the scheduling task. When a disturbance occurs on the shop floor, social negotiations help schedulers to solve problems (Higgins, 1996) with, for example, the customer department (for due dates), the maintenance department (for maintenance periods), and the production department (for overlapping or dividing manufacturing orders).

Table 5

Proportion of types of goal formulated during scheduling stage ($\overline{N}$ is the mean frequency). On average, novices formulated 4.2 goals and experts formulated 4.7 goals.

	Novices		Experts	
	Mean	Standard deviation	Mean	Standard deviation
Minimizing makespan	0.50	0.20	0.20	0.22
Minimizing job lateness	0.25	0.16	0.17	0.15
Minimizing waiting time	0.15	0.16	0.47	0.26
Introducing margin to anticipate maintenance	0.10	0.16	0.16	0.34
Total	1.0 ($\overline{N}$ = 4.2)		1.0 ($\overline{N}$ = 4.7)	

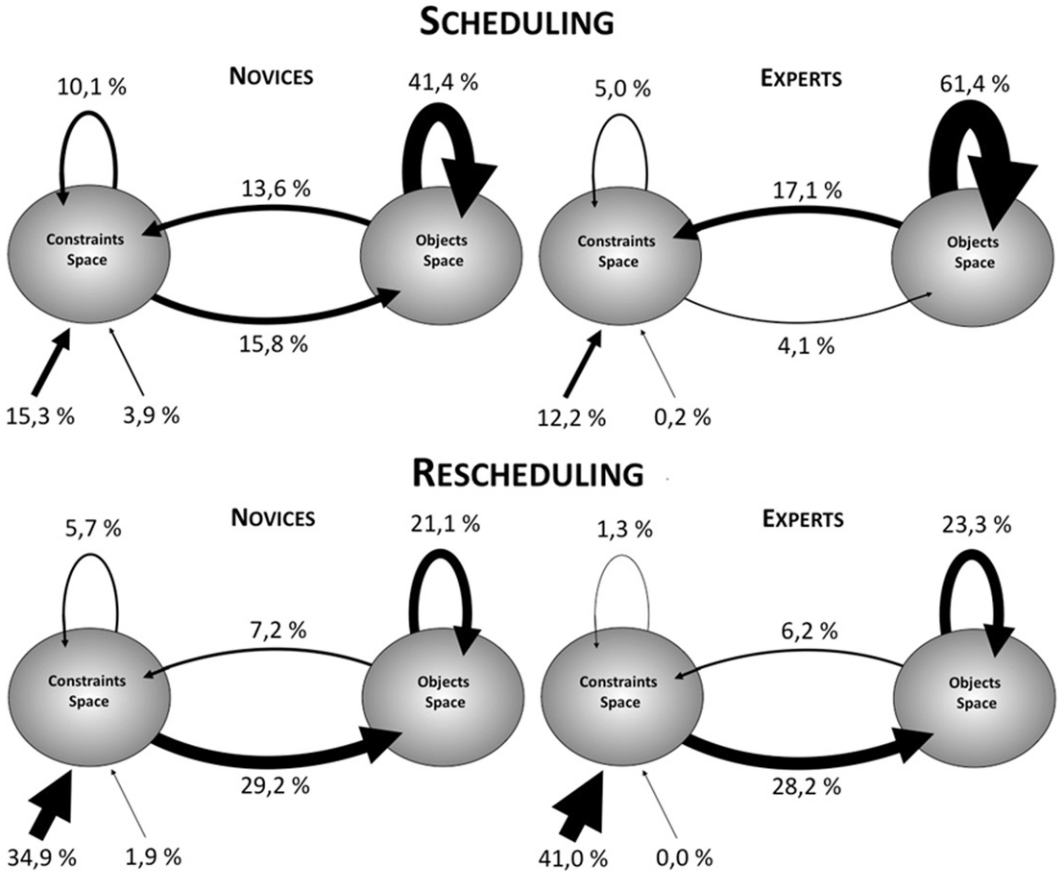

Fig. 3. Relations between spaces for novices and experts for the scheduling and rescheduling stages. The arrows represent a ratio of operations (predicates).

Negotiations enable the scheduler to have more flexibility and to relax constraints, particularly when there are conflicts between goals (Stoop and Wiers, 1996). In this experiment, the participants were unable to negotiate. The appearance of constraints about periods of maintenance (rescheduling task) produced conflicts with due dates, because the participants were unable to satisfy the constraints simultaneously (a feature of the task). In order to find an acceptable solution with a limited cognitive cost, experts

Table 6
Summary of results (percentage). All differences between experts (E) and novices (N) are significant and notable.

Level of control	Scheduling – first axis: high level of control (goal formulation and evaluation) vs. low level of control (constraint formulation, propagation and satisfaction)	High level of control: E > N
	Rescheduling – First axis: high level of control (constraint violation, goal formulation and evaluation) vs. low level of control (constraint formulation, propagation and satisfaction)	High level of control: E > N
Strategic operations vs. tactical operations	Rescheduling	Strategic operations: E > N
Types of goal formulated	Scheduling	Minimizing makespan: E < N Minimizing waiting time: E > N
Operations implying the constraints space vs. operations within the objects space	Scheduling	Constraint formulation from preferences: E < N Constraint propagation: E < N Constraint satisfaction: E < N Object modification: E > N
	Rescheduling	Constraint formulation from specifications: E > N Constraint formulation from preferences: E < N Constraint propagation: E < N
Direct transitions from a constraint formulation	Scheduling	Transitions to strategic activities: E > N Transitions to tactical activities implying constraints: E < N
	Rescheduling	Transition to strategic activities: E > N Transition to tactical activities implying constraints: E < N

decided to violate constraints of maintenance. Thus, experts favored one goal (no delay for customers) at the expense of another one (maintenance of the machine) because of conflicting goals (Higgins, 1996; Mietus, 1994; Tabe and Salvendy, 1988). In this task it seems that experts preferred to negotiate with the maintenance department than with the customers.

Experts performed fewer constraint management operations than novices, particularly constraint propagations (H2). While experts executed more object modification (within-OS operations), especially during the scheduling stage, novices appeared to rely more heavily on constraint propagations. In other words, experts are more likely than novices to handle objects, i.e. representations on the Gantt chart, that enable greater visibility of constraints, which are more abstract. This wider usage of the required external representation formats by experts than by novices validates the hypothesis that the externalization of mental representations is a characteristic of expertise (Hoc and Amalberti, 2007).

Finally, although we found individual differences in level of control and in object management between experts and novices, it was not possible to draw inferential conclusions with regard to performance quality. However, there was a notable difference during rescheduling for the criterion of “total lateness”, which is better for experts. This difference is closely linked to favoring the due date at the expense of the constraints of maintenance, as stated previously.

Although this study of industrial scheduling was taken from a textbook case, the results were relevant to a better understanding of expertise in scheduling. In the study by Hoc et al. (in press), the description of the nature of expertise in university timetabling, as a particular case of scheduling, showed the same feature of a greater willingness for mental representation externalization by experts in comparison with novices. Experts had a wider usage of the required external representation formats (objects) than did novices. In this study of expertise in an industrial scheduling task, it was argued that the ability to externalize mental representations appeared to be an invariant of expertise, with the aim of alleviating the workload. With similar results, the cognitive control model proposed by Hoc and Amalberti (2007) also seems to be relevant to the study of scheduling. This model was developed to describe different modes of dynamic situation management in which uncertainty is an important component. Uncertainty is also a major feature of industrial scheduling situations (Akkerman and van Donk, 2009; Higgins, 1996; McKay et al., 1988). Future work could focus on this feature, with a controlled ecologically valid task.

However, two major differences between university timetabling and industrial scheduling do exist, whatever the expertise level. First, in timetabling, it was noted that management of constraints was proportionally much more important than strategic aspects (action plans). In industrial scheduling, even if the tactical dimension is also proportionally more important than the strategic dimension (goals and procedures), the proportion is slightly different from the one noted in timetabling: thus, strategic aspects are proportionally more important in industrial scheduling than in timetabling. This result shows that timetabling is less routinized than industrial scheduling. In industrial scheduling, standard algorithms (EDD for Earliest Due Date, LPT for Longest Processing Time, etc.) are the basis for the implementation of action plans. This was certainly one of the reasons for Sanderson (1991) to focus on the procedural models of the human scheduler. In the present study, which examines industrial scheduling, the use of this kind of procedure has been highlighted, along with the management of declarative plans (formulation and evaluation of goals). In this manufacturing situation, we noted that the strategic dimension was more important (about 40% over average whatever the expertise level) than was the case in timetabling (about 12% above average, whatever the expertise level).

Second, it was noted that, in timetabling, the management of constraints was proportionally much more important than the management of objects, whatever the expertise level. This distribution is different in industrial scheduling where the parts played by constraint management and object management are about the same. It is possible that this difference between both situations is based on the characteristics of the task in terms of number of constraints to be managed. In timetabling many constraints had to be taken into consideration by the schedulers, such as availability of rooms and teachers, sequence of teaching module, association between the type of room and type of teaching module, and duration of teaching module. In the industrial scheduling task, the number of constraints to be managed was less important: duration of the operations, delivery dates, and sequence of operations. Constraints of maintenance were also added to the phase of industrial rescheduling. The introduction of these new constraints had an effect on the distribution of the operations: the part played by operations implying objects decreased compared to operations that implied constraints. This effect confirms our hypothesis.

9. Conclusion

In an industrial context, it is almost impossible to adopt an optimal schedule because the problem is made up of such a large number of aspects, all of which need to be taken into account (NP hard problems). A computer system, and a real-time support system in particular (Kuo and Hwang, 1998), must help schedulers to manage the complexity of such problems. In this study, we showed that experts use a higher level of control (more abstract). The question is one of finding a suitable abstraction level to guide the scheduling activity, thus reducing the complexity of the situations (number of constraints). This computer system could bear on the OS, because experts are able to extend their cognition toward objects (external cognitive control). Future research work must be conducted with the same ergonomic perspective, because developing decision support for scheduling tasks is interesting both from a theoretical and practical viewpoint. A deeper understanding of problem solving and decision-making processes in scheduling is needed. In order to design an efficient human–computer system, the interface must facilitate the switch between internal and external representations. Higgins (1996) criticized the use of a Gantt chart because, he argued, this display does not show the whole information that an operator may use to design a schedule; thus, it does not support the decision-making processes (e.g., inference, pattern recognition). Studies by Sanderson (1989) and Hoc et al. (2004) highlighted the importance of the perceptive property of the interface in terms of a perceptive suggestion for a solution. As stated by Trentesaux et al. (1998), it may be of interest to explore the work of Vicente and Rasmussen (1990) on ecological interface design. The aim of these interfaces is to make visible any relevant information for the operator. For that purpose, the abstraction hierarchy is used to determine the constraints that should be displayed on external supports, which are compatible with several levels of processing. By using these interfaces, schedulers can do more than just see a solution to a scheduling problem; they are able to calculate a solution.

Finally it is important to specify that the scheduler’s task is to design a schedule rather than to execute it. Therefore, one of the scheduler’s roles is to contribute to the prescription of work on the shop floor (machines and workers). For example, in this study, experts favored the maximization of machine utilization over the total duration of the schedule. In other words, they favored minimizing workers’ free time over faster production. Scheduling decisions have an effect on workers; thus, it is important to understand the problem-solving processes of schedulers. From the perspective of designing an efficient human–computer system, such ergonomics-based recommendations must be taken into account in the design of production systems (Jensen, 2002).

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Appendix. Illustrations of predicates

Predicates	Arguments	Examples
Strategic operations		
PR-FORM		*"I'm going to arrange the manufacturing orders from the shortest to the longest"*
	Procedure	SPT: Shortest Processing Time
GOAL-FORM		*"I'm going to consider due dates in order to obtain the very least lateness as possible"*
	Goal	Minimizing job lateness
GOAL-EV		*"There is a lot of margin, machines are not completely used"*
	Goal	Minimizing waiting time
	Evaluation	Negative
CTR-VIOL		*"Finally, I'm not going to integrate the first maintenance on the welding machine"*
	Origin	Prescribed
	Manufacturing order	Not relevant here
	Machine	Cutting
	Period	Period
Tactical operations		
Transition operations from the specifications, the designer's preferences or the Objects Space toward the Constraints Space		
CTR-FORM		*"The duration of the welding stage for the MO 6 is 80 min"*
	Origin	Prescribed
	Manufacturing order	6
	Machine	Welding
	Period	Duration
Operations within the Constraints Space		
CTR-PRG		Combines two previous constraints: "*The duration of the MO 1 is 400*" Coded: CTR-FORM (*prescribed*, *MO1*, <machine>, *duration*) "*The due date of the MO 1 is 400*" Coded: CTR-FORM (*prescribed*, *MO1*, <machine>, *due date*) To deduce that "*the MO1 must be schedule in first*"
	Origin	Deduced
	Manufacturing order	1
	Machine	All
	Period	Position (first)
Transition operations from the Constraint Space to the Objects Space		
CTR-FEAS		*"The period of maintenance for the cutting machine is OK"* In this example, the scheduler considers satisfied the constraint about one period of maintenance
	Result	Feasible
CTR-SATF		By moving an MO to another period, the scheduler is satisfying a constraint previously formulated
Operations within the Objects Space		
OBJ-MOD		The scheduler is moving an MO to another period without expression of any constraint

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