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A cognitive typology of scheduling situations: a contribution to laboratory and field studies

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Scheduling activities are carried out in the domains of industry (production scheduling), personnel (nurse scheduling) and transportation (train scheduling). Nevertheless, there is little available knowledge on how operators schedule. In general, laboratory studies have been found to be not entirely representative of real situations (i.e. there are problems of ecological validity). Furthermore, it is difficult to make generalizations because field studies are usually conducted with just one scheduler. To overcome these two issues, this paper suggests bringing laboratory and field studies closer together using a cognitive typology. First, typologies that do not explicitly refer to a cognitive point of view are discussed. Second, the properties of a cognitive typology are detailed. A cognitive typology specific to scheduling situations is presented. This typology associates seven dimensions with their related human strategies: complexity; uncertainty; time pressure; cycle synchronicity; process steadiness; process continuity; multiple and contradictory objectives. For each dimension, the theoretical, methodological and practical implications are detailed.

Keywords: Cognitive typology; Ecological validity; Scheduling; Planning; Complexity; Uncertainty

1. Introduction

Cognitive ergonomics has developed around an interest for computer-related work situations. Consequently, in the past, it has sometimes been placed within a broader human–computer interaction (HCI) framework. Whilst it is still part of HCI today, it cannot, however, be entirely constrained within this framework. Indeed, the introduction of issues related to Work Psychology has broadened its interests to include interactions between humans and their cognitive work environment as a whole (Green and Hoc 1991). In this way, cognitive ergonomics has developed multidisciplinary approaches to complex situations in order both to describe and explain implied cognitive mechanisms.

Scheduling is a particularly complex activity. From the point of view of the mathematical theory of complexity, it is considered an NP-Difficult problem. One can define the operator's activity as the elaboration of a plan for other actors (machines, operators), based on the allocation of tasks and taking into account both

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temporal constraints (waiting periods, precedence, etc.) and those constraints related to the usage and availability of the necessary resources. The elaborated schedule usually covers several weeks or months. Since scheduling itself can take a human operator several hours or even several days (Crawford *et al.* 1999), it differs from, for example, air traffic control. Moreover, scheduling is not only a design activity, it also encompasses other activities, such as the development of interpersonal and favour networks or acting as an information hub (Jackson *et al.* 2004).

In addition, the situations that necessitate schedules are diverse, ranging from production scheduling in manufacturing to the elaboration of train schedules or hospital staff rotas. This diversity of situations highlights the inadequacy of generalizations based on very specific field studies or taken from laboratory studies that are not representative of real practices.

Many field studies have been carried out on only one operator because, although interaction with other operators can take place, in most cases, scheduling is an individual activity. Whilst large quantities of data have been gathered, these studies lack a priori hypotheses and eventually this leads to generalization problems. This is because in the human scheduling activity it is not possible to distinguish between what is due to individual characteristics (expertise, training, cognitive style, motivation and so on) and what is due to environmental properties (the complexity to be managed, for example). Existing case studies, therefore, do not provide a significant understanding of the way scheduling is carried out. For this reason, Sanderson and Moray (1990) summarized human scheduling in field studies with an uncompromising quotation by Cassidy *et al.* (1985, p. 12): 'We do not completely understand the relation between human factors and manufacturing production, except on an anecdotal basis'.

In addition, scheduling studies carried out in a laboratory aim to operate in controlled situations and with numerous individuals in order to make it possible to attain statistical significance. Almost all laboratory studies in scheduling have been carried out with novice individuals (particularly students of production control). However, for the majority of laboratory studies, few claims are made by the authors as to their ecological validity; that is to say, the quality of reproduction of conditions compared to those in real situations (Hoc 2001). So it is often impossible to determine if the studied situation reproduces conditions that actually exist. Thus, criticism of laboratory studies often relates to their ecological validity. For example, Sanderson (1989) noted that, in a study carried out by Ben-Arieh and Moodie (1987), participants maximized their performance to meet the objective measured in the experiment, whilst at the same time ignoring other important performance criteria, even though these were essential in practice.

Therefore, when it comes to generalizing results, scheduling literature is trapped between field studies that are often limited to anecdotal results and laboratory studies that show poor ecological validity. For this reason, the contribution of scheduling studies to the improvement of practices is very weak, as Crawford and Wiers (2001, p. 30) noted: 'How can academic planning and scheduling knowledge aid and influence planning and scheduling practice when as a research community we cannot offer generalized findings about human performance in this area?'

Consequently, no study can significantly contribute to the theoretical foundations of human scheduling unless it is based on a conceptual framework, which makes it possible to take into account both the representativeness of laboratory experiments (their ecological validity) and the representativeness of the results obtained in the case studies (the possibility of transferring these results to other situations). This point, which was also noted in a review by Hoc *et al*. (2004), has led these authors to suggest that future progress must be made on a theoretical level, moving beyond the usual references to formal models of scheduling.

In this way, a typology of scheduling situations can make it possible to resolve the tensions that exist between field and laboratory research. As Webster (2001a) noted, whilst a scheduling study considered on its own cannot constitute a generalization applicable to all scheduling situations, all studies taken together can direct research towards the most relevant points. The elaboration of a typology of scheduling situations should make it possible to consider field and laboratory studies in a broader context. Such a typology may make it possible to decide on the transfer of results from one field study to another. Moreover, the need for a typology has been stressed by many previous reviews of human factors in scheduling (Crawford and Wiers 2001, MacCarthy *et al*. 2001, Hoc *et al*. 2004).

The first section of this paper considers further justifications for the role of a typology in scheduling situations as well as reasons for selecting a cognitive typology (and not a typology by domain, for example). This will then lead to the presentation of a cognitive typology that is specific to scheduling situations and that is based on the existing scheduling literature. The section concludes with the resulting theoretical, methodological and practical progress for laboratory and field studies.

2. Towards a cognitive typology of scheduling situations

2.1. *Some attempts to determine a typology of scheduling situations*

A literature review of human scheduling studies leads to the immediate agreement with Crawford and Wiers (2001) concerning the wide dispersal of published journal papers. Beyond the disciplinary differences between research communities (mainly ergonomics, engineering, computer science and operational research), publications are also distributed according to the domain under consideration. Three main domains have been extensively studied: industrial (e.g. scheduling in a car factory); personnel (e.g. the scheduling of nurse rotas); and transportation (e.g. train scheduling). This division, in fact, constitutes a typology that is centred on the domain and thus makes it possible to distinguish three main classes of problems. However, whilst distinguishing between situations from within different domains enables one to study the possibility of transferring knowledge from one domain to another, this point of view does not adequately discriminate between the activities of the human schedulers. For example, scheduling strategies carried out by a human operator in a car factory may be closer to those carried out for hospital nurse scheduling (i.e. discrete process, many disturbances to the schedule, contradictory objectives) than to those carried out in a steel factory (i.e. continuous process, fewer disturbances and clearer objectives). For this reason, domains do not constitute relevant dimensions through which operator activity can be described and predicted. Thus, it is important to establish a typology that makes it possible to discriminate human strategies more precisely.

Other typologies have been suggested within the scheduling literature, especially those that centre on the machine. MacCarthy and Liu (1993) and Liu and MacCarthy (1996), for example, have put forward a typology that suggests that situations be described according to several dimensions (for example, capacity constraints of the machines or scheduling performance criteria). The goal of this kind of characterization is to provide a description of the situations (especially in the industrial domain) in order to compare scheduling algorithms. However, this is a machine-centred approach because it does not take into account the presence of human operators in scheduling. For this reason, from a human perspective, the identified dimensions may not be appropriate. Furthermore, designing automated scheduling independently of human competences is incompatible with the possible optimization of human–machine performance. Yet hybrid approaches to scheduling (associating human and machine) always demonstrate better performances than those carried out by human or machine alone (Haider *et al.* 1981, Sanderson 1989, Chen and Hwang 1997). Since this kind of typology excludes human operators from the decision loop, it cannot be relevant to the discrimination of situations from a human point of view.

A typology of scheduling situations that takes into account human factors does exist. (In this paper, the term 'situation' is favoured over the term 'task'. A situation is considered as the interaction between a task and a human. For example, complexity is not only seen as a property of the work environment but also as a human characteristic, e.g. expertise in the task.) The typology suggested by Wiers (1997a) associates both the human and the work environment. Situations are categorized into one of two dimensions: the presence (or not) of disturbances and the possibility of the scheduler recovering (or not) from these disturbances. Developed in several papers (Wiers and McKay 1996, Wiers and van der Schaaf 1996, McKay and Wiers 2001), this typology attempts to determine the allocation of tasks between the human and the machine, focusing on those task demands that influence operator strategy (i.e. disturbances). However, scheduling tasks cannot only be considered in terms of the presence (or not) of disturbances, since other factors also influence schedulers (such as varying levels of complexity or uncertainty). This typology may fulfil its goal of attempting to determine the allocation of tasks, but it does not comprehensively detail scheduling activity in relation to task demands or the support tools necessary to meet these task demands. Therefore, it cannot be used as a framework of analysis to bring field and laboratory studies closer to each other, which is this paper's main goal.

2.2. *Reasons for a cognitive typology*

The first two typologies presented in the previous section centred on the domain or on the machine. They are, in fact, inadequate for finely discriminating between scheduling situations because they do not take the human factors perspective into account. Moreover, as previously noted, the typology presented by Wiers and colleagues is not sufficiently detailed to really take into account the variety of task demands. A cognitive approach should allow situations to be precisely outlined from a human point of view and go on to explain the implied cognitive mechanisms (van der Schaaf 1993). Hoc (1993) considered three criteria that justify the use of a cognitive typology. These criteria, together with examples related to scheduling situations, are presented below.

2.2.1. A theoretical reason. A cognitive typology makes it possible to describe the situations according to factors that will directly determine the operators' strategies. For example, in the case of a dimension associated with the structural complexity of the process (detailed in § 3.6), Cowling (2001) presents an illustrative situation: when the order list is full (what could be defined, from a cognitive point of view, as high structural complexity), the schedulers' strategies are directed towards the maintenance of production flow by avoiding delays caused by changing produced components. On the other hand, when the order list is not as full (i.e. lower structural complexity), the schedulers focus on production quality. So the use of a cognitive typology makes it possible to characterize situations (as a list of dimensions) on the basis of their implications for operators' strategies.

This descriptive property makes it possible to verify the ecological validity of experiments in laboratory settings. As a matter of fact, it becomes possible to determine the properties of existing situations and thus to investigate new laboratory studies in order to evaluate their ecological validity. Moreover, because a typology associates conditions (dimensions) with the resulting operators' strategies, it is possible to predict the strategies for new case studies and eventually to compare them with previous results. This predictive property makes it possible to compare different case studies, starting from operators' strategies rather than from surface properties related to the application domain. Thus, for example, it becomes possible to compare results from a new case study about hospital staff scheduling with those from a case study of industrial scheduling with similar dimensions (e.g. discrete process with disturbances that imply rescheduling, and so on).

2.2.2. A methodological reason. The methods used to analyse operator activity depend on various dimensions of the typology. For example, when time pressure is high, the use of simultaneous verbal protocols should be avoided: they could overload the operator's task to the extent of strongly distorting their activities because the task already requires a high cognitive workload (Smith and Crabtree 1975, Sharit and Salvendy 1987).

2.2.3. A practical reason. Finally, a cognitive typology could aid the design process; for example, helping to decide on the optimal task allocation between human and machine (and level of automation) or helping to guide the design of an interface (van der Schaaf 1993). The relevance of a cognitive typology to the design of support tools has also been suggested by Rasmussen (1992) and Rasmussen *et al.* (1991). This is even more crucial in scheduling situations because of the large number of different interfaces available (Gibson and Laios 1978, Higgins 1999, Cegarra 2004) and the subsequent need to understand more precisely the support needs of the human scheduler.

However, although these three criteria are justification for a cognitive typology, most existing cognitive typologies are generic; in other words, they can be applied to a large number of situations (e.g. Hoc 1993). Currently, there is no specific typology of scheduling situations.

3. A cognitive typology of scheduling situations

The typology presented in this section refers to existing literature on the development of cognitive typologies (Hoc 1993, van der Schaaf 1993) and is based on cognitive typologies with a generic aim (Amalberti 1996, Cellier 1996, Funke 2001, Quesada *et al*. 2005). Subsequently, this scheduling typology has been tested on different case studies (in particular, in the book edited by MacCarthy and Wilson 2001) in order to refine the dimensions. Indeed, many of these case studies include very detailed descriptions of the tasks carried out by schedulers in very specific situations and make it possible to precisely discriminate between situations that appear closely related in a generic typology.

The description of dimensions will be presented through data derived both from laboratory and field studies. Whilst the number of published studies from industry means that examples of situations will often refer to this domain, human operator strategies should not be seen as only related to this domain. Furthermore, this paper will mainly focus on studies based on expert schedulers. When results originate from novice schedulers, additional information on their relevance for expert schedulers will be suggested.

In addition, this typology does not take into account some dimensions suggested in generic typologies. This is the case with the control scope of the temporal span, even though it could modify human strategies. The reason is that scheduling must be considered on an intermediate level between production planning (high level) and dispatching (low level): this excludes the longest and shortest temporal production spans from the control scope of schedulers (cf. McKay and Wiers 2003 for a discussion of the temporal span of scheduling). Finally, seven main dimensions are identified: complexity; uncertainty (of information and of the future state of production); time pressure; cycle synchronicity; process steadiness; process continuity; multiple and contradictory objectives. These seven dimensions will be examined successively.

3.1. *Uncertainty (of information given and of the future state of production)*

According to many authors, uncertainty is a fundamental component of scheduling problems (e.g. McKay *et al*. 1989). The human scheduler appears crucial for the management of two different types of uncertainty: uncertainty about the information given (to the scheduler) and uncertainty about the future state of production.

There are multiple sources of uncertainty about the information given. For example, Bermejo *et al*. (1997) studied schedulers that obtained information about the quantities of products and due dates that was not completely correct. The strategy of the schedulers to manage this uncertainty was simply to seek other sources of information. However, when no other source of information exists, performance may be affected. The consequences of such uncertainty can be illustrated by an experiment carried out by Laios (1978) and referred to by Sanderson (1989): schedulers' performance is at its best when the date of provisioning is certain rather than completely or partially uncertain.

Generally, computers are a common source of uncertainty about the information available. One reason is that a scheduling tool has a more constrained view of production compared to that of a human scheduler (Jüngen and Kowalczyk 1995, Simons 1999). Moreover, supplying data to a computer can be a difficult or a costly process. In this way, Valax and Cellier (1992) noted that the more a scheduling computer tool acts as a constraint (for example, requiring long computing times for each update), the less operators supply small but costly changes in production to this tool (and these are not integrated into the calculations). Consequently, the differences between the contents of the computer database and the reality of the workshop lead to new uncertainties about the schedule. This can also mean that human schedulers usually look for other sources of information. For example, Webster (2001b) noted that a scheduler specifically searches for differences between the information contained in the computer database and the reality of the workshop (e.g. a shop-floor operator may have forgotten to indicate the end of an order on the computer).

This point is particularly important in relation to the *practical implications* of this typology. Scheduling support tools generally do not have a representation of the degree of certainty of their own information. This can lead to an illusion of certainty (for the machine) and can possibly result in human operators eliminating solutions that they would not normally eliminate. Instead, support tools have to offer better ways of displaying the levels of certainty of information in order to allow the scheduler to look more efficiently for other sources of information.

The second type of uncertainty relates to the future state of production. This uncertainty results from either incomplete knowledge of the situation (for example, the inability to predict specific novel tasks or the absence of staff) or disturbances in production (as detailed in § 3.2). To deal with such uncertainty, the scheduler tends to make scheduling more precise in the short term and less precise over the long term (Valax and Cellier 1992, Bermejo *et al.* 1997). Indeed, for the operator, it is often rather inconvenient to schedule in detail for a long time span because there is always the possibility that the schedule may have to be changed following an unexpected event (Dessouky *et al.* 1995). This human strategy of postponing decisions until a more convenient time could be termed least-commitment scheduling, referring to studies in Artificial Intelligence (e.g. Stefik 1981).

Another approach to dealing with this uncertainty, identified by Thurley and Hamblin (1962, quoted by Sanderson 1989), is to build schedules that are robust enough to withstand disturbance. In the same way, McKay *et al.* (1995b) noted that schedulers are able to build robust scheduling by using more than 100 different heuristics to tentatively anticipate problems. In another paper, McKay *et al.* (1995a) describe a scheduler who assigns these operations to the least flexible resources with the intention of preserving the most flexible resources for later rescheduling. In relation to the *methodological implications* of this typology, Crawford *et al.* (1999) elaborated a structured interview method in which schedulers are questioned with different decision probes in order to build a decision diagram in situations where there is uncertainty. This method may allow for a better understanding of the way humans manage uncertainty and, in particular, the elaboration and selection of heuristics for robust scheduling.

There are two ways of dealing with uncertainty that relate to the future state of production: least-commitment scheduling and robust scheduling. Schedulers may favour one strategy over another depending on the complexity dimension that will be detailed in § 3.6. The next section presents another factor that may contribute to this uncertainty, process (un)steadiness.

3.2. *Process steadiness*

Many authors have noted that the human operator is an essential element in the management of disturbances to the schedule (e.g. Bi and Salvendy 1994, Hume *et al.* 1995). In operational research, the term uncertainty is used to characterize situations that contain disturbances. According to this approach, in the formal (mathematical) model, the occurrence of events is uncertain. In this paper, uncertainty will only be associated with the human point of view and the term unsteadiness will be used to describe a process in which there are disturbances. The reason for this distinction is that what is unknown for a model is not necessarily uncertain for an experienced operator. For example, schedulers could anticipate that the upgrade of a resource will not function perfectly and could, therefore, insert idle time if they thought problems may occur (e.g. McKay *et al.* 1989, O'Donovan *et al.* 1999). Therefore, if disturbances can be perfectly anticipated, steadiness has to be distinguished from uncertainty about the future state of production.

When the process is steady, the scheduler's main task is to reduce the level of uncertainty about current information. By increasing their knowledge about the current state (i.e. decreasing uncertainty), schedulers can improve their performance. There are few later adjustments of the schedule in a steady process (McKay and Wiers 2001). In this way, Dutton and Starbuck (1971, quoted by Starbuck 1987) noted that schedulers seek to maximize the objectives (in their situation, the use of the machines) and use heuristics to predict the production time of orders. Scheduling models usually consider a process to be steady (McKay *et al.* 1988). It is, therefore, also easier to support the human scheduler in steady situations because the support tool can use a model that is highly relevant to the process.

When the process is unsteady, there are two different ways of managing this unsteadiness, depending on whether or not the same operator is also managing disturbances (rescheduling). In most situations, there is only one operator for both scheduling and rescheduling. In these cases, reactive scheduling could account for up to 90% of the daily work of a scheduler (McKay and Wiers 2001).

Another way to manage unsteadiness, especially in large companies such as rail operators, is to run two services: one that builds a long-term schedule (for the following year) and one that updates the current one (Kiewiet *et al.* 2005). Such an allocation particularly highlights the need for efficient cooperation: either between human operators, with each one being in charge of part of the task (scheduling or rescheduling), or human–machine cooperation, with the machine usually in charge of the scheduling task. In relation to the *practical implications* of this typology, when a computer is in charge of scheduling and one human operator is in charge of rescheduling, it is particularly important to prevent failures in cooperation. This is the case with the *complacency* problem (Mosier and Skitka 1996, Hoc 2000), which leads even those operators who are aware of the limits of the scheduling algorithm to accept the schedule because of the (cognitive) costs associated with the modification of this computer-generated schedule (Cegarra and Hoc 2006). In relation to the *methodological implications*, Kiewiet *et al.* (2005) also detailed a method that compares the mental models of operators in charge of scheduling and rescheduling. This could provide a better understanding of the specific differences in scheduling and rescheduling strategies in human–human cooperation.

Therefore, it is important to consider whether an operator is in charge of scheduling only, rescheduling only or both scheduling and rescheduling.

For example, results from studies where an operator only manages disturbances (rescheduling) cannot be transferred to studies in which the operator is only elaborating the schedule. Indeed, predictive activities are not of the same nature as reactive ones.

3.3. *Time pressure*

Even an experienced human operator requires a lot of time to build a schedule. Crawford *et al.* (1999) noted that scheduling may involve hours and even days of work. To carry out this same scheduling in a limited time, for example, when the operator has to immediately insert a new urgent order in the production schedule, could introduce a very high mental workload on the operator (Moray *et al.* 1991). The problem of time pressure is usually not a part of scheduling situations, except in very specific situations. This is the case, for example, in the scheduling of hospital surgeries when urgent surgery takes precedence and may require the whole schedule to be changed.

In the presence of time pressure, operators generally favour more schematic decisions (Sanderson and Moray 1990, Crawford and Wiers 2001). To deal with time pressure the operator can, indeed, proceed to shorter-term strategies that are more reactive and less costly from a cognitive point of view, but which imply a reduction of the anticipation span. In this way, Tulga and Sheridan (1980) showed that when subjects had to follow several orders simultaneously, they could reduce their workload by focusing on a crucial part of the task whilst at the same time decreasing the temporal span taken into account. Schedulers could also reduce the number of evaluated solutions or carry out more schematic evaluations of the possibilities; that is to say, sacrifice the precision of the solution for speed. However, according to Dessouky *et al.* (1995, p. 450): 'such trade-offs should not be left to intuition but should, as far as possible, be rationally determined, and subjects should be trained explicitly to adopt the most appropriate strategy'. In relation to the *methodological implications*, it also means the analysis method does not have to be intrusive and, for example, concurrent verbal protocols have to be avoided (as noted in § 2.2).

Time pressure leads to short-term strategies in relation both to temporal span and the number of alternatives taken into account. It often results in bad performance, which can be measured by productivity (Trentesaux *et al.* 1998), by behavioural performance, through the detection of its own errors (Liu and Wickens 1994) or by cognitive workload (Moray *et al.* 1991). Furthermore, the scheduler's performance is worse when structural complexity is high (the complexity dimension is presented in § 3.6). However, in relation to cognitive workload, Bi and Salvendy (1994) claimed that time pressure exerts less influence on a scheduler's cognitive workload than does complexity.

Human limitations in managing time pressure have led Liu *et al.* (1993) to suggest leaving the operator to supervise automation when there are high levels of time pressure; in this role in particular, the operator is better at detecting errors. This is why time pressure problems are occasionally posed in terms of operator training (e.g. Dessouky *et al.* 1995) but more generally in terms of support tools (e.g. Sanderson and Moray 1990). In relation to the *practical implications* of the typology, this indicates the need to support schedulers using interfaces that do not require many (cognitive) resources. For example, Trentesaux *et al.* (1998) suggested using an *Ecological Interface Design* (Rasmussen *et al*. 1994), which directly displays the relevant constraints for making a decision. However, first tentative attempts by Krosner *et al*. (1989) and then Kinsley *et al*. (1994) to build such an interface for scheduling problems indicate that there are specific problems to be taken into account. More recently, Higgins (1999) developed an ecological interface that still requires some empirical validation but could be a basis for the design of scheduling interfaces, helping operators to manage time pressure more efficiently.

Finally, when there is both time pressure and uncertainty (this dimension is presented in § 3.1), Sheridan (1988) noted a paradoxical result: time pressure could reduce uncertainty. The reason is that, above a certain level, the arrival of new tasks offers an opportunity to look ahead to the evolution of the process. Bi and Salvendy (1994, p. 227) concur, noting that: 'The longer the queuing line, the further the subject could look ahead, and the less the uncertainty'.

3.4. *Cycle synchronicity*

Several authors have noted the presence of multiple temporal cycles in scheduling (e.g. Sanderson and Moray 1990; Crawford *et al*. 1999); for example, there are production cycles (for machines and/or operators), maintenance cycles and so on. These cycles can evolve from different time spans, as can be illustrated in the scheduling of farm work, where different cycles exist. As highlighted by Cellier and Valax (1995), in addition to milking the cows (production) and tending the animals (maintenance), there is also a dynamic related to the evolution of production during the year, with periods of high load (June, July) and of low load (November, December). In this case, cycles are also asynchronous as they evolve in different time spans (days, weeks, months, years). Moreover, cycles are not only asynchronous due to the time span but also due to their rhythms (e.g. production rate). For example, a machine could have a fixed rhythm, whereas shop-floor operators have different rhythms due to inter- and intra-individual variability. The scheduler could take advantage of this; for example, Lane and Evans (1995) noted that when there is some unresolved problem in the schedule, the scheduler could select a highly proficient shop-floor operator to manage the problem during a critical moment (in this way, increasing the production rate).

When there are many asynchronous cycles, it may be very difficult for the scheduler to have a relevant mental model of the situation. According to Sanderson (1989), it is difficult for humans to associate independent events in order to anticipate a situation because operators have to simultaneously observe several sources of information in order to integrate the elements and to estimate the state of the production system. So, asynchronous cycles could contribute to uncertainty about the future state of production, as Trentesaux *et al*. (1998, p. 350) noted: 'The overall effect of this problem [multiple cycles] is to make it very difficult for an operator to deduce the state of the system, and the greater the degree of automation, the harder the task of the operator'.

Therefore, in order to produce an adequate schedule, it is necessary to have knowledge of each cycle; thus, the presence of asynchronous cycles increases the complexity of the task. In relation to the *methodological implications* of this typology, this indicates that methods relevant to the study of complexity management could also be used; for example, an analysis of cognitive workload according to the number of asynchronous cycles. In this way, Haider *et al.* (1981) noted that scheduling performance is highly sensitive to the level of variability of the situation (indicating the presence of asynchronous cycles).

The *practical implications* of this dimension suggest several consequences for the design of a support tool. First, one of the most important cycles to be taken into account is that of the scheduler. For example, there could be specific moments when schedules are built (e.g. a specific day each week or each month) and there could be some moments when the schedule cannot be updated (e.g. during the night when the scheduler is away). Moreover, Sanderson (1991), Crawford *et al.* (1999) and then Berglund and Karltun (2006) have noted that the human operators are often interrupted during scheduling. By studying schedulers' cycles it may then be possible to identify support needs (e.g. allowing automatic rescheduling after disturbances during the night, or supporting schedulers in their recovery after an interruption).

Second, the existence of asynchronous cycles in production also influences the design of scheduling tools. Webster (2001b), for example, notes that a scheduling tool can impose constraints on the start-up of an operation if that operation cannot finish because of other factors: for example, the tool cannot schedule an operation at the end of the weekend or at the beginning of maintenance. However, the human scheduler is not constrained by such factors and has a better knowledge of cycles; that is to say, the human operator knows that tasks allocated on Friday evening can be finished on Monday morning by the shop-floor operators.

3.5. *Process continuity*

When it comes to studying continuous processes, it is particularly advisable to distinguish between process control and the scheduling of this process. For example, studies of blast furnace controllers (e.g. Hoc 1989) are not relevant to understanding human scheduling carried out in a steel factory where there are one or more blast furnaces. The blast furnace controller is just one element of a larger production process, whereas schedulers manage the whole production process. Therefore, human scheduling always relates to discrete units (although the process may, at first, be continuous).

When studying scheduling, results derived from discrete processes cannot be easily transferred to continuous processes and vice versa. First, from a theoretical point of view, there is an important difference between the scheduling of discrete and continuous processes. Fransoo and Rutten (1994, p. 51–52) define a process as continuous, 'if individual items are undistinguishable from each other (like oil, chemicals) or if the products are simple and produced in very large quantities such that it does not make sense to distinguish them individually (like glass bottles, aluminium cans)'. Second, as Sanderson (1989) noted, human strategies will differ according to process continuity and, therefore, it is advisable to take this dimension into account. In fact, process continuity will mainly modify human scheduling in relation to two other dimensions: complexity and time pressure.

With regard to the complexity dimension, continuous processes are generally characterized by small quantities of products that have to be managed simultaneously, by small numbers of different products and by a fixed routing (Fransoo and Rutten 1994). Routing is particularly limited because there are no-wait constraints and a limited use of buffer resources. This is due to the fact that, once started, products have to be finished, especially in the case of perishable materials (Crama *et al.* 2001). For example, in the steel industry, liquid steel from the furnace has to be used quickly, otherwise it would cool down. So, the complexity of continuous processes is generally lower than for discrete processes and mainly relates to resource constraints.

In discrete processes, schedulers often evaluate performance using due dates, whereas in continuous processes they favour product quality. Moreover, in a continuous process any production problem is quickly visible because it has direct consequences on the remaining production (Trentesaux *et al.* 1998). For example, Barfield *et al.* (1986) suggest that a local disturbance (e.g. a machine that is unavailable) in production will generally block the whole production process. On the contrary, in a discrete process, a disturbance does not constrain the system as a whole and its effect could only appear after several hours or days of production (Sanderson 1989). However, the point noted by Sanderson (1989) is, at the same time, a characteristic of the control of slow continuous processes (Hoc 1989). This indicates a need for further studies of human strategies in relation to process speed, being careful to distinguish scheduling from process control.

In relation to the time pressure dimension, continuous processes (as studied in scheduling) are generally characterized by a high production speed (Fransoo and Rutten 1994); this puts time pressure on the scheduler. According to Sanderson (1989), in the case of discrete processes, the operators are characterized by a more qualitative approach, determining a tendency starting from a set of discrete states.

In relation to the *practical implications* of this dimension for the design of support tools, the control of discrete and continuous processes indeed requires different interfaces, especially for diagnosing disturbances and evaluating performance. In this way, Usher and Kaber (2000) have noted that a hierarchical task analysis could be particularly relevant for elaborating guidelines for the design of scheduling interfaces. Moreover, in relation to the *methodological implications*, this could facilitate the identification of the schedulers' information needs in order to understand more precisely how humans evaluate the performance of the process.

3.6. *Complexity*

Scheduling is a complex task (considered NP-Difficult from a mathematical point of view); nevertheless, humans are found to be generally very good at this task. However, scheduling requires long periods of time (as noted in § 3.3). In this way, many authors have noted that up to 90% of this time is devoted to the identification of the relevant constraints, with only 10% spent on building the schedule (Fox and Smith 1984, Grant 1986, Sanderson 1989, Crawford and Wiers 2001). Thus, the scheduling task is sometimes considered only in terms of complexity management for the human operator.

Taking transportation as an example, the elaboration of train schedules for one region is not of the same structural complexity as scheduling for a whole country. This is due to the fact that each station has specific constraints that will reduce the degrees of freedom of the whole schedule. This is also true in the case of industrial scheduling, as noted by Hwang *et al.* (1983), where humans can be in control of a limited number of machines simultaneously. However, as Quesada *et al.* (2005) have pointed out, the number of variables that have to be controlled is, in fact, not a very good indication of (cognitive) complexity. This is because the more resources (e.g. machines or staff) available, the greater degrees of freedom that exist. For example, Lagodimos *et al*. (1996) noted that the situation they studied required 2 days for two operators to schedule 19 resources for the next week. However, this duration is not only related to the number of resources, but also to the number of orders to be produced. For example, assigning one operation to one of 19 resources is usually easier than scheduling 19 operations to only one resource.

So, complexity also relates to the production load, because the higher the number of orders to be managed simultaneously, the more complex is the task (Bermejo *et al*. 1997). Bi and Salvendy (1994) name this complexity the *schedule tightness*. This also implies risk because a high production load leads to difficulties in rescheduling after disturbances (Valax and Cellier 1992). Furthermore, the schedulers take into account constraints that are not prescribed. In this way, McKay *et al*. (1995b) noted that schedulers take into account implicit constraints: personal (how the shop-floor operators accept the work pressure), environmental (impact of the climatic conditions), social (period of absenteeism, etc), infrastructure (moment when the procedures, the personnel or the materials used change) and so on.

When evaluating the complexity of a situation, two characteristics have to be taken into account, namely, the structural complexity and tightness of the schedule, whilst at the same time focusing on the constraints that humans really do consider.

In order to manage this complexity, schedulers could favour more abstract strategies, such as the categorization of situations or the detection of perceptual configurations. Dutton's (1964) paper, as cited by Sanderson (1989), offers an example of categorization. In this study, schedulers reduced complexity (defined as having more than one billion possible schedules) by dividing customer orders into eight main categories. Categorization in itself is also an interesting way to identify the nature of expertise in scheduling (Cegarra 2004). The scheduling interface could also directly evoke solutions from similar cases. The ability of schedulers to use perceptual configurations from the interface to access abstract values is well noted (Sanderson 1989, Dessouky *et al*. 1995, Cegarra and Hoc 2004). In terms of the design of efficient interfaces, this is particularly important in relation to the *practical reasons* for this typology.

As demonstrated by Bi and Salvendy (1994), scheduling complexity results in cognitive workload and, after a critical point, this leads to a degradation of performance. Yet, schedulers switch strategies in accordance with the level of complexity (Tabe *et al*. 1990). This highlights the need to consider the efficiency of scheduling strategies (i.e. taking into account both the performance of the strategy and its cognitive cost).

Furthermore, schedulers look for satisfactory performance rather than for an optimal one. For example, Cowling (2001) noted that schedulers spent several hours building a schedule that covered the next 8 hours. Even so, both schedulers and senior managers admitted that all relevant constraints were not satisfied in this scheduling. However, this ability to use satisfactory (and not optimal) strategies allows schedulers to perform well, even in very complex situations.

In this way, one strategy often used comprises the relaxation of constraints to obtain new degrees of freedom (Camalot and Esquirol 1998, Higgins 1999, Crawford and Wiers 2001). For example, finishing one order late could allow several others to be finished on time. Human strategies of constraints relaxation are often noted in field studies, although little is known about their usage (McKay *et al*. 1995a).

Here, one has to distinguish between two cases of unsatisfied constraint. This could be an indication of an error in the usual sense; for example, O'Neil *et al*. (2002) noted in a study of airport schedulers that an expert assigned an incoming plane to a gate that is not used for arrivals. Another case of unsatisfied constraint could be carried out deliberately; for example, a scheduler could use resources (notably machines) in a non-standard way to increase short-term capacity or put an order in late to finish several others in time. In relation to the *practical implications* of this typology, this also indicates that a support tool has to let the scheduler decide on the flexibility of the constraints. Whilst the tool could inform the scheduler about constraints that are not satisfied, the scheduler should make the final decision.

Finally, complexity leads to a high cognitive workload for the scheduler and this workload will reduce anticipation abilities. This could explain why some authors have noted that human schedulers are not able to anticipate a situation more than half an hour ahead (e.g. Crawford and Wiers 2001). This dimension could also explain why schedulers favour least-commitment scheduling instead of robust scheduling when there is uncertainty about the future state of the workshop. In fact, from a cognitive point of view, least-commitment scheduling is more economic than robust scheduling as it reduces the need to anticipate long-term evolution of the schedule. In relation to the *methodological implications* of this typology, this highlights the need to study cognitive workload in relation to complexity. In this way, the study by Bi and Salvendy (1994) is particularly relevant as it forms the basis for understanding the different dimensions that influence cognitive workload in scheduling, most notably complexity, and could be extended to take into account all the dimensions presented in this paper.

3.7. *Multiple and contradictory objectives*

It is extremely difficult to measure scheduling performance because of the number of different objectives (Gary *et al*. 1995, Wiers 1997b). Moreover, it is sometimes impossible to design a schedule that can satisfy all of the potentially contradictory objectives (Dessouky *et al*. 1995). For example, the various services within the same company could favour a number of different objectives: shop-floor staff measure performance using throughput, whilst commercial staff use sales volume and delivery performance, and senior managers favour production costs and customer satisfaction (e.g. Cowling 2001). Scheduling is an important activity because it is the last opportunity to settle multiple and contradictory objectives.

Moreover, objectives management cannot be solely restricted to the point of view of the organization; it should also integrate the objectives that the human scheduler seeks to satisfy (Sanderson and Moray 1990, MacCarthy *et al*. 2001). For this reason, the multiplicity of objectives relates to the complexity dimension because the operators must solve different objectives at the same time and this adds to the schedulers' work. For example, Wiers (1996) noted that schedulers could satisfy short-term objectives in scheduling and, at the same time, ignore long-term objectives. This gave operators the opportunity to decrease their workload by reporting part of the task at a more suitable time (i.e. least-commitment scheduling).

In addition, contradiction between objectives is often noted in practice. Higgins (1996) noted in his study that operators tried to maximize the use of the machines and to minimize delays: such objectives are, in fact, contradictory since the minimization of delays requires machines to be available. Where objectives are contradictory, the literature remains limited and very little is known about human strategies. Usually, the literature indicates that human schedulers are able to manage contradictory objectives (e.g. Higgins 2001). A study of the management of contradictory objectives in scheduling also states that the adopted strategies are close to those relating to the reduction of uncertainty (Cegarra 2004). In relation to the *methodological implications* of this typology, this also indicates that methods for the uncertainty dimension are relevant to studies that feature situations with contradictory objectives. In this way, the structured interview method presented by Crawford *et al.* (1999) could allow the study of the management of both uncertainty and contradictory objectives. Furthermore, this is consistent with the study by Lipshitz and Strauss (1997), which indicates that conflict between alternatives is a form of uncertainty that is usually solved by weighing up the pros and cons. In accordance with this assertion, experimental studies indicate that human schedulers weight some objectives more favourably than others. In particular, many authors note that schedulers favour objectives that are related to due dates instead of those related to shop utilization. This was noted in the case of novices and experienced operators (Tabe and Salvendy 1988, Tabe *et al.* 1990, Valax *et al.* 1990), using a graphical (Cegarra 2004) or a textual (Haider *et al.* 1981) interface.

This finding also has implications for the design of a scheduling support tool, as it is sometimes suggested that scheduling should be allocated to a computer tool using weighting from human schedulers (e.g. Lagodimos *et al.* 1996). In relation to the *practical implications* of this typology, it is advisable to support schedulers in managing multiple and contradictory objectives and, at the same time, allow them to be responsible for objectives weighting. One way of supporting schedulers in this task is to offer relevant feedback of their performance (Davis and Kottemann 1995). However, many scheduling situations do not offer any feedback to the scheduler; for example, when modifying train timetables, operators in charge of rescheduling have no information about the quality (e.g. robustness) of this change. Displaying feedback on the support tool could also allow a better balance of short-term and long-term objectives.

4. Conclusion

Three reasons have been put forward as to why there is a need for an elaboration of a cognitive typology of scheduling situations. The theoretical reason aims to list dimensions that discriminate operators' strategies; for example, least-commitment or robust scheduling (uncertainty dimension), short-term scheduling (time pressure), categorization (complexity) or weighting strategy (multiple and contradictory objectives). In this way, this paper successfully deals with the issues raised by Sanderson (1989, p. 651), namely that: '[...] there is no underlying theory of how certain environmental parameters should affect human schedulers relative to scheduling rules. More systematic work needs to be done on what aspects of system configuration influence human scheduling abilities and how they exercise their influences'. However, more studies are needed to identify schedulers' specific strategies according to cycle synchronicity and process continuity dimensions (see Appendix A).

The methodological implications of this typology are that one's interest is directed towards the variety of methods used, in accordance with the dimension. This is the case with the study by Crawford *et al.* (1999), in which an interview method was used to precisely analyse situations with uncertainty and/or contradictory objectives. This is also the case with the cognitive workload analysis for complexity (and cycle synchronicity) dimensions undertaken by Bi and Salvendy (1994). A further methodological implication is a recommendation to avoid concurrent verbal protocols when there is time pressure. Finally, the method used by Kiewiet *et al.* (2005) could be particularly interesting when it comes to comparing operators' strategies; for example, comparing scheduling and rescheduling strategies. Indeed, there is no requirement to use a very specific method for each dimension. But this typology could create a better link between the methods and the theoretical knowledge available, since a method cannot be selected independently of a theoretical background.

Practical implications include the interpretation of the dimensions of the typology in terms of a support tool (and its interface) for the operators. Several suggestions have been presented: limiting the illusion of certainty by offering information about the certainty level (uncertainty dimension); limiting complacency and more generally human–machine cooperation failures, when the operator is only in charge of rescheduling (process steadiness); taking into account scheduling cycles in support tools (cycle synchronicity); reducing cognitive workload by making decisions using graphical displays (time pressure); facilitating the management of complexity by displaying abstract information (notably when the process is discrete), letting the scheduler decide which constraints are flexible; and, finally, displaying relevant feedback on the interface to allow multiple and contradictory objectives to be handled better. Through these different suggestions, it is possible to direct research towards supporting human scheduling more efficiently.

Finally, the theoretical advances of this typology could bring field and laboratory studies closer together within the same theoretical framework. This will also make it possible to prevent scheduling, as a field of interest, from being limited to either field or laboratory studies by indicating mutual contributions from each point of view. For example, Crawford *et al.* (1999, p. 67) considered field studies to be more relevant: 'we would suggest that there really is no other way to understand cognitive performance in a context-based activity such as manufacturing scheduling'. However, by only considering field studies, these authors cannot escape the general criticisms aimed at the Naturalist Decision Making (NDM) approach. For example, Lipshitz *et al.* (2001, p. 345) noted that NDM has been criticized as being 'soft' (Yates 2001): 'This appears to mean that researchers do not adhere to the methods and standards appropriate for laboratory-based experiments'. As this paper indicates, results from experimental studies with a control of ecological validity could also offer relevant knowledge about human scheduling in relation to well-identified dimensions. Therefore, the use of this cognitive typology should make it possible to control the ecological validity of new laboratory studies by comparing results with those anticipated by the typology.

In the same way that scheduling problems are best considered from a multidisciplinary approach, associating, for example, Cognitive Ergonomics and Operational Research, both field and laboratory studies are necessary for a precise understanding of human scheduling.

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Appendix A. Summary of the theoretical, methodological and practical implications of the cognitive typology

Dimension	Theoretical implication (identified strategies)	Methodological implication (suggested methods)	Practical implication (suggested support tool)
Uncertainty	Seeking other sources of information; Least-commitment or robust strategies	Interview method	Implementing options to figure out the certainty level
Process steadiness	Reactive scheduling (unsteady process)	Comparison of the representations of schedulers and reschedulers	Particularly preventing complacency and failures in human–machine cooperation
Time pressure	Short-term scheduling; Reducing number of evaluated alternatives	Avoiding concurrent verbal protocols	Graphical displays reducing the cognitive workload
Cycle synchronicity	(related to uncertainty and particularly to complexity)	Analysis of cognitive workload	Including scheduling cycles in the tool
Process continuity	(related to complexity and time pressure)	Identification of information under consideration for evaluating system performance	Facilitating the diagnosis of disturbances and the evaluation of performance
Complexity	Categorization; Detection of perceptual configurations; Relaxing constraints	Identifying the constraints that are really considered; Studying expertise through categorization; Measuring cognitive workload	Designing interfaces that facilitate the identification of perceptual configurations. Letting the scheduler decide on the flexibility status of constraints
Multiple and contradictory objectives	Weighting strategy	Interview method	Designing relevant feedbacks

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