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Temporal decision making in complex environments

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The basic hypothesis of the author is that under the influence of technological development and market pressure, situations take on temporal characteristics that are more and more difficult for the operator to control. The temporal strategies traditionally installed by the operator disappear, are transferred or transformed.

Far from counterbalancing these phenomena, the displays, as they are designed in the workplace, obliterate the temporal dimension. The errors that are seen to appear are the product of a mismatch between the characteristics of the situation and the operator's resources. Four mechanisms of time estimation are discussed. Field study results on temporal strategies, such as anticipation, assessment of a process evolution and planning adjustment are developed.

1. Introduction

(*a*) *The two faces of Janus*

Time, like the two faces of Janus, is at once a diagnostic tool and an element of complexity for man in dynamic environments. Today's research in continuous processes favours the complexity by emphasizing the existence of temporal errors and fixations: this is to say errors where the operator persists in a wrong course of action, or a wrong situation assessment, in the face of opportunities to revise (De Keyser & Woods 1989). This orientation masks to some extent the ways in which time contributes to the establishment of order in the environment: strategies and references used by the operator to improve his diagnosis are passed over in silence; but above all, insufficient emphasis is placed on the severe deficiencies of information displays in control rooms. Our basic hypothesis is that:

(i) under the influence of technological development and market pressure, situations take on temporal characteristics that are more and more difficult for the operator to control. The temporal strategies traditionally installed by the latter disappear, are transferred or transformed;

(ii) far from counterbalancing these phenomena, the displays, as they are designed in the workplace, obliterate the temporal dimension;

(iii) the errors that are seen to appear are the product of a mismatch between the characteristics of the situation and the operator's resources.

(*b*) *Profound changes in the control of continuous processes*

Over the past two decades, profound changes have occurred in the control of processes, and as a result they have modified not only the operator's role in the control room, his objectives and actions, but his knowledge as well. The principal modifications are shown below.

(i) *Modification at the automation level and of the system's computer structure*

A greater control of the parameters of industrial systems has allowed for a more stable automation and a larger computerization. The dynamic control of the process has gone further and further away from the operator, as well as the possibility of optimizing the parameters or diagnosing the incidents.

Many continuous processes now function according to the law of all or nothing; the system is stopped when it goes out of order and only the highly specialized teams for maintenance of quality control can intervene.

A greater emphasis is placed on recovery from incidents than on their prediction.

(ii) *Integration of the process into a larger and more highly interconnected system*

The processes have been widely integrated and made more complex. This renders them more vulnerable (Perrow 1984), and also more difficult to bring under control. As some of the fact always remain unknown to the operator, his understanding of the situation can never be complete.

(iii) *Modification of information displays*

The computerization of control rooms has brought with it the appearance of visual display screens giving a sequential information to the operator. These have replaced the mimic boards covering the walls of the control room that allowed a synoptic view of the system. Direct conversations by interphone between the operator and the specialized teams on the terrain often serve to supplement these displays.

(iv) *Different management methods*

New methods of management based on the clients' requirements have created the conditions for a different style of management and a 'just in time' planning. The disappearance, in most corporations, of stock, the emphasis on the economical challenge, and the rigorous time control are the new facets of the industrial game. The operator has more responsibility but is under more pressure.

However, if the operator's basic modes of time estimation are not modified, then they are integrated in different strategies. There is less control of the process, but more supervision of production. The operator keeps at hand only the transient conditions that are difficult to bring under control temporally. He manages a vast system in which he does not understand many of the indicators. With less diagnosis and more recovery, greater emphasis is placed on the prediction of the efficiency of actions than on an analysis of the origin of incidents. Based on the customer's requirements, a tight planning results that needs to adjust clock time with the process evolution.

2. Temporal estimation and characteristics of the work situation

(*a*) *The mechanisms*

Empirical studies (Decortis 1988; Van Daele 1988, 1989) and cognitive psychology experiments (Piaget 1946; Montangero 1979) provide the principal mechanisms that help to understand how people deal with time. Beside these mechanisms, the clock-time estimation intervenes as a metric.

(i) *Causal, or physical estimation*

The content of the elapsed events is used to evaluate time duration. The relationships established by the operator between velocity, space and time, correspond to the covariation of the physical system. This estimation mode is based on causality, and the time appears to the operator, as a time of action, that is incompressible if the given of the problem, speed and space, does not change. These mechanisms can only be used if the operator has a deep knowledge of the system, and if he has access to necessary information.

(ii) *Logical estimation*

The onset and the duration of the events are deduced from their relations with other events. The durations are perceived as intervals without causal content, only the beginnings and ends of intervals are meaningful for the subject. For instance, an operator could decide to start up a delicate procedure once the maintenance work has been finished. This mode of estimation is highly economic, it can be described as a 'temporal heuristic'. But it requires a sufficient saliency of cues, and the existence of other events for a relational structure to take place.

(iii) *Internal estimation*

Temporal regulations in man and animals have revealed the ability to learn rhythms and to estimate occurrences of events and durations that appear regularly. As the working situations are usually very familiar to the operators, they seem to gradually internalize more aspects of the environment with experience. But this subjective time estimation is the more exposed to possible temporal distortions.

These mechanisms of time estimation are used by the operator in varying degrees, and quite often he combines all of them in the same reasoning process. The preference given to one over another depends on the characteristics of the situation, the task, the information displays, and his own expertise. But another mode of time estimation, heterogeneous to the other ones, comes into play. It is the clock-time.

(iv) *Clock-time estimation*

Clock-time introduces into the situation a time that is exterior to both the action and the subject. It can be used as a convenient metric in some cases, but very often it creates a source of adjustment and tension. Most of the processes have to be run within temporal limits, and the operators have to match continuously the time of action and the clock-time.

(*b*) *The characteristics of the work situation*

De Keyser (1988) and Decortis *et al.* (1989) have described the work situations as a temporal structure of events, process events and human actions. The nature of the links, the occurrence of the events, their saliency are the temporal attributes. The new role of the continuous process operator is to integrate these events in parallel. We will focus the discussion on three temporal strategies of the operators: anticipation, assessment of the process evolution and planning adjustment.

3. Temporal strategies

(a) Anticipation

Since the 1960s, numerous studies carried out on continuous processes have brought to light a temporal strategy used quite frequently by operators: anticipation (Iosif 1968, 1969; Kortland & Kragt 1980). Anticipation is an oriented behaviour that permits the operator to get ahead of the event with a deftness and precision that often amazes the outside observer. Iosif best brought this strategy to light with his *in situ* analysis of operators of thermoelectric plants. He distinguishes two forms of anticipation:

(i) a probabilistic anticipation: the operator scans the parameters on the mimic board before they go out of order. He does this in a selective manner, 'as if', says Iosif, 'he has internalized the statistical structure of the board'; as if he had prior knowledge of the probability of appearance of breakdowns;

(ii) a functional anticipation: the operator predicts that a parameter will go out of order based on the variation of another one which is functionally connected to it.

In this research, the main indicator of the operator's performance was the relation between the time when the information was taken by the operator and the disturbance. To discuss the current validity of this work, two elements of the work situations that have been reported must be brought up. (*a*) Studies were carried out in control rooms where mimic boards were still being used. Iosif's work is based essentially on the associations the operator makes between the variations of the dials; on the emergence of covariation patterns with which he associates the states of the system. These patterns are not 'learned' in the framework of a training session, but rather are 'discovered' gradually by the operator. As the operator's practice accumulates, he assimilates rarer and differentiated patterns. (*b*) In these studies, the operator has kept, within his attribution, control of the process in case of an incident.

This research is already part of the past, for today anticipation has been profoundly transformed. The increasingly reduced action the operator takes on the process has brought about a decrease in consultation of the information displays, in spite of the large numbers remaining in the control room. As a result, the operators gain a much weaker knowledge of the process. A comparison of operators of the same technological steelmaking process, but at different levels of automation (De Keyser 1987) shows to what extent a high level of automation decreases the operator's knowledge of events. Not only do they misdiagnose incidents but, it is important to note, they do not attempt to anticipate them. This temporal strategy, which is brought up so often in the literature, has not completely disappeared; but has merely been transferred. The operator no longer has much to do with the process, but he has as an implicit task to manage a more vast system that encompasses the teams on the terrain, the transports and the relations with the forward and rear posts. This is where incidents can arise for him, and these are the incidents he tries to anticipate.

In anticipation, internalization and logical time estimation seem to be the main mechanisms. But the operator can no longer observe the actions of the team because of geographical constraints and he has only very poor instruments at his disposal for estimating the links that connect actions and events. Telephones and interphones are thus the preferred channels of this type of information – as described in field studies by Van Daele (1989). But the information he obtains in this way is far from precise and mentally costful, even if socially welcome.

(*b*) *Assessment of the process evolution*

Past research on the follow-up of evolutive processes especially emphasized the tasks of tracking. Today the action the operator takes on the process is being cut back; and apart from the manual control he exercises during transient conditions, the system evolves at least partially without him. Whenever the operator ceases to focus his attention on the anticipation of events, he continues to be very attentive to the supervision of the system changes. Indeed, it is during these moments that he makes decisions and coordinates actions.

In an electric powerplant, De Keyser *et al.* (1989) have studied the start-up process, comparing the knowledge and the performance of engineers and operators. They have recorded all the flow of behavioural traces, taking information from the displays, actions performed on the process, verbalizations, etc. during a 30-hour period.

The structure of these traces reflects the dynamics of the process, but also the expertise of the subjects. For both engineers and operators they reveal the existence of temporal envelopes. They are clearly shown by breaks, stops and more intense moments of information taking, which emphasize and punctuate the process evolution. We can distinguish two kinds of temporal envelopes.

(i) Temporal intervals, limited by indicators, which can be associated with relatively stable and known states of the process. All of the operator's attention is thus placed on the transitions and on the changes of state.

(ii) Temporal patterns, that is to say envelopes during which the parameters develop in a form known to the operator that he checks at regular intervals. They present interesting characteristics that distinguish them from intervals: these are personal constructions. They cannot be related directly, to specific states of the system. The breaks that the operator makes in the continuity of the system are his own. For him they correspond either to inflexion points of parameters, that he links to an action, or to critical values of variables which he must go through. But the operators and the engineers do not have the same patterns: those of the engineers seem to be more economic, more consistent with less checking, than those of the operators. The more practice the operators have, the better they are able to distinguish between subtle variations of state, by using appropriate cues. The prediction of the evolution of a process is thus internalized up to a certain point and monitored regularly by a checking. But without a causal model that would allow them to understand the evolution, rather than predicting, the operators anticipate certain indicators. Comparing the behaviour of pilots and expert monitors in transitory conditions, Amalberti *et al.* (1989) find the same results: they interpret the caution of the pilots and their numerous checkings as a fear about leaving a known temporal pattern. In a similar analysis, expert monitors prove to be much more audacious and consult the information displays less often.

The assessment of the process evolution seems to be characterized by the use of logical time estimation, building a nest of temporal envelopes to capture the dynamics of the environment. If these envelopes do not contain causal knowledge of the situation, if they are just shells, the operator does not seem able to really predict the future. Rather than predicting, he anticipates the apparition of indicators. And he tries to maintain himself in the limits of a known pattern. This is where we can see the advantage of intelligent aids that simulate an evolution of the process and the possible effects of certain actions. Such aids are still rare to this day. The limitations of these aids are bounded to the complexity of the situation. But certain situations

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are intrinsically complex and cannot be represented satisfactorily with mathematical models; in which case the operator prefers to rely on his own solid but hardly powerful experience, rather than to refer to an undependable mathematical model.

(c) *Planning adjustment: when to act?*

One of the most challenging tasks of an operator in a dynamic environment is to discover when he has to act. For the effects of an action can be totally different, if performed too early or too late. But the right time is not the clock-time: it depends upon the precise state of the process evolution. If the operator has a strong causal model of the process, he can manage himself by looking to cues he has related previously to specific changes of state. But the displays are rarely designed to provide this information in a form suitable for the operator. Even gradients, so useful to control the dynamic evolution of a plant, are usually not available on screens. When the operator has to intervene, not on the process but in the management of the system, the task is far more complex: the actions of the teams on the floor are not observable.

Very often the problem seems to be resolved by the existence of an organizational planning, which fixes the temporal structure of the system, and distributes the roles. Currently, new forms of management accentuate this tendency, providing the operator a computerized model. But the model does not include the incidents and the specific conditions of a given situation. In a continuous casting, Van Daele (1989) shows that 67 % of the planning programs estimated by the computer were corrected by the operators before being started. The corrections are not inversions of the sequence order of actions, rather, they are contractions or dilations of durations so as to take into account in advance the possible incidents of the system. They are, however, limited and concern a single post; where, according to the operators, the technical risk connected to the modification of duration was lower.

If planning requires a clear temporal limit, the operator must combine, in a causal manner, the metric of the clock with definite durations of actions. All of this expertise consists of estimating the possible adjustments between these two times, minimizing the risks, and taking into account the causal constraints of the system. It is clear that he hesitates to change the order of actions, or to cancel some of them. He does not seem to adopt opportunistic strategies, such as described by Hayes-Roth & Hayes-Roth (1979), may be because the mental workload entailed by this mode of planning is high (Valax 1985). But we can bring up another explanation. Many authors have represented the form of knowledge included in planning as schemata. But unless the operator has experimented himself with the effect of his actions, he is rarely certain about the links he establishes between events. Are these sequential links, or links of causality? In highly integrated industrial systems, any change has repercussions which spread. The operator acts very little; but when he does act, he limits his intervention to what he can keep under control.

Choosing the right moment to act, adjusting a fixed plan to the dynamics of the situation, are highly complex strategies. They often require a deep knowledge of the situation including the causal links between events and actions. The introduction of the clock-time in this game, far from simplifying the strategies, adds an element of complexity. The new intelligent aids designed to assist the operator in these tasks begins to advise him on what to do, but still remain silent about when to act.

4. Discussion and forms of errors

The operator bases his temporal strategies on the checking of cues, they thus have to be visible. His pinpointing is focused on the critical phases of the system's evolution, where he still has to perform actions. As the technological development has delocated his traditional area of actions, from the process to the whole system, the non-visibility of the team actions increases the complexity of his task. But what kind of knowledge is encompassed within the temporal envelopes? The rhythm of the checking follows the dynamic evolution of the system; it is not exclusively the result of an internal clock. But what really suggests a knowledge is the semantic of the choice of the cues: these are samples of the critical parameters of the system at the very moment of the checking. Which parameters are really critical is a subjective matter: operators and engineers differ in their choice. The operators seem to be more cautious; their checking contains three types of parameters: (i) the critical parameters from a functional point of view; (ii) the unreliable parameters; (iii) the parameters giving the state of the system's elements they do not understand very well. This abundance in the checking reflects their awareness of knowledge and control limitations. If they have schemata of most of the usual situations, and this is what the behavioural traces and the verbalizations suggest, they have a bad envisioning of the future of the system. This is especially the case when notions such as gradients and exponential evolutions are brought into play. However, in intrinsically complex situations, there is no mathematical model to predict the future state of the system, and if these situations frequently occur, the operators finally succeed in finding adequate behavioural responses to control them.

Many studies have tried to demonstrate the superiority of one type of knowledge over another one: the theoretical knowledge of the engineers versus the practical knowledge of the operators. The results of such comparisons have always been ambiguous and spurious. They have neglected to take into account the interactions between the knowledge and the characteristics of the situation; they have ignored the successful efforts developed by the operators to compensate for the gaps in their educational background by the use of checking and redundant mechanisms of time estimation.

But temporal errors exist. They can occur for trivial reasons. Disturbance of basic mechanisms of time estimation, lack of attention, etc. These errors could be assimilated to 'temporal slips' (Reason 1989). More interesting are the systematic errors resulting from a mismatch between the operator's cognitive resources, the displays and the situation. From the body of errors that we began to put together two years ago, four critical situations have been isolated: they are situations where only one mechanism is to be used, because of the nature of the task. If in these situations, there is a lack of cognitive resources or of displays, systematic errors occur.

The current technical evolution accentuates the risk of those mismatches. The redundancy of the temporal mechanisms is not favoured by the displays; the clock-time is omni-present. The intrinsic character of complexity of the industrial environment is underestimated by the designers: mathematical models are supposed to control all the cases. Training is rarely focused on temporal aspects, and the difficulties to dynamically integrate an extended and heterogeneous system, composed of interconnected modules, are entirely obliterated. There is very little effort made in communication networks (Falzon 1989), in intelligent decision supports and in modelling.

These contradictions lead to a stress increase for the operator who must attempt to offset the system's deficiencies. In certain cases, he does not succeed; and if his failure brings about a catastrophe, there is nothing more to do than to invoke 'human error'. This magical term covers all in its shadow: the situation, the displays, the designers, and the public is partially reassured.

References

Amalberti, R. *et al.* 1989 Développement d'aides intelligentes au pilotage: formalisation psychologique et informatique d'un modèle de comportement du pilote de combat engagé en mission de pénétration. *Rapp. CERMA* **49**.

Decortis, F. 1988 Dimension temporelle de l'activité cognitive, lors de démarrages de systèmes complexes. *Travail hum.* **51**, 125–138.

Decortis, F., De Keyser, V., Cacciabue, P. C. & Volta, G. 1989 Temporal dimension of man–machine interaction. In *Human–computer interaction and complex systems* (ed. G. R. S. Weir & J. L. Alty). London: Academic Press.

De Keyser, V. 1987 Structuring of knowledge of operators in continuous processes: case study of a continuous casting plant start-up. In *Human error and new technology* (ed. J. Rasmussen, J. Leplat & K. Duncan). London: John Wiley & Sons.

De Keyser, V., Richelle, M. & Crahay, M. 1989 The nature of human expertise. *Tech. Rep. Pol. Sci. Belg.* (Programme I.A., June 1989).

Falzon, P. 1989 *Ergonomie cognitive du dialogue*. Grenoble: Presses Universitaires de Grenoble.

Hayes-Roth, B. & Hayes-Roth, F. 1979 A cognitive model of planning. *Cognitive Science* **3**, 275–310.

Iosif, G. 1968 La stratégie dans la surveillance des tableaux de commande. I. Quelques facteurs déterminants de caractère objectif. *Revue roum. Sci. Soc.* **12**, 147–163.

Iosif, G. 1969 La stratégie dans la surveillance des tableaux de commande. II. Quelques facteurs déterminants de caractère subjectif. *Revue roum. Sci. Soc.* **13**, 29–41.

Kortland, K. & Kragt, H. 1980 Process alarm as a monitoring tool for the operator. Third International Symposium on Loss Prevention and Safety Promotion in the Process Industries. Basle, September 15–19.

Montangero, J. 1979 La genèse des raisonnements temporels. In *Du temps biologique au temps psychologique* (ed. P. Fraisse). Paris: Presses Universitaires de France.

Pedersen, S. A. 1989 Coping with complexity by abstraction and idealization. Presented at the ESPRIT-MOHAWC Workshop. Riso, Roskilde, February 7–9.

Perrow, C. 1984 *Normal accidents*. New York: Basic Books.

Piaget, J. 1946 *La développement de la notion de temps chez l'enfant*. Paris: Presses Universitaires de France.

Reason, J. 1989 *Human error*. Cambridge University Press.

Valax, M. F. 1985 Cadre temporel et planification des tâches quotidiennes. Ph.D. thesis. Université de Toulouse-le-Mirail.

Van Daele, A. 1988 L'écran de visualisation ou la communication verbale? Analyse comparative de leur utilisation par des opérateurs de salle de contrôle en sidérurgie. *Travail hum.* **51**, 65–79.

Van Daele, A. 1989 Dynamic decision making of control room operators in continuous processes: some field study results. In *Comtemporary ergonomics 1989* (ed. E. D. Megaw). London: Taylor and Francis.