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Gunnar Johannsen
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Henk G. Stassen

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Gunnar Johannsen 1), Alexander H. Levis 2), and Henk G. Stassen 3)

1) Laboratory for Man-Machine Systems (IMAT-MMS), University of Kassel (GhK), D-3500 Kassel, Germany
2) Dept. Electrical and Computer Engineering, George Mason University, Fairfax, VA 22030, USA
3) Man-Machine Systems Group, Delft University of Technology, 2628 CD Delft, The Netherlands

Abstract. This survey paper focusses on the main theoretical issues in today's man-machine systems research and applications. The following problem areas are discussed: (1) modelling human performance and mental workload, with identifying the state of the art as well as major methodological difficulties; (2) task allocation and decision support, with a human-centred perspective on cooperative problem solving, integrated automation, and distributed decision making in teams; (3) man-machine interfaces, with outlining some presentation and dialogue issues; (4) design problems, with stressing the need of early active participation of man-machine-systems specialists and the usefulness of guidelines; and, finally, (5) evaluation and experimental validation, with covering laboratory and field evaluations, with covering laboratory and field evaluations, experimental design and validation, as well as model-driven experimentation. The importance of man-machine-systems contributions to the design of better technical systems and their user acceptability is emphasised.

Keywords. Man-machine systems; human performance modelling; mental workload; task allocation; decision support; integrated automation; distributed decision making; Man-machine interfaces; human-centred design; experimental validation.

1. INTRODUCTION

The complexity of industrial processes has enormously been increased during the last decades. This tendency originates from a number of reasons, such as

- the scale enlargement of modern plants,
- the required specifications dealing with the product quality, the energy conservation, the environmental pollution control, and the safety of the plant, and finally
- the progress in process control and informatics creating totally new possibilities.

This essential change in process operation has led to the definition of new human operator tasks. In just two decades, human manual control became much less important and human supervisory control developed as the main concept for man-machine interactions. The tasks of the human supervisor are predominantly cognitive ones, and contain at least the following six subtasks [Sheridan, 1980, 1992]:

- the monitoring of all data presented to the human supervisor,
- the learning and interpretation of the data presented,
- the process tuning or set-point control or teaching of the process in normal circumstances,
- the intervention into the process for instance during abnormal process conditions,
- the fault management during malfunctioning of the plant, and finally,
- the planning, such as for starting-up and shutting down the plant.

All the above changes in complexity and requirements of industrial process plants, in automation concepts and technologies related to new systems, computer and software engineering approaches, as well as in the tasks of the human operator(s) showed the evidence of a number of theoretical problems in man-machine systems more clearly. Concepts of cognitive engineering and human-centred design approaches evolved as possible answers to these problems. They suggest that human information processing behaviour as well as knowledge and goal structures of the human operator(s) have to be investigated. The results need to be applied in advanced automation and decision support systems as well as in advanced man-machine interfaces, in order to guarantee enough flexibility and job satisfaction for the human operator(s) which are prerequisites for safe systems operation.

A discussion session with the same title as this survey paper was held during the 11th IFAC World Congress at Tallinn, Estonia, in August 1990. The three authors of this paper and S. Franzén from Sweden were the panelists in that discussion session. This survey paper includes some of the material presented at Tallinn, but further elaborates it and tries to focus on the main theoretical issues in today's man-machine systems research and application. Particularly, the following problem areas were identified:

- modelling human performance and mental

workload,
- task allocation and decision support,
- man-machine interfaces,
- design problems, and
- evaluation and experimental validation.

These problem areas will be discussed in the subsequent sections of this paper. Evaluations and/or experimental validations of suggested improvements in man-machine systems are indispensible because, at last, we are dealing with an applied and experimental field of research and development when trying to contribute to better man-machine systems in industrial and public domains.

Methodologies to evaluate and to validate human behaviour have been developed in great detail in manual control. However, the state of the art is totally different in supervisory control [Stassen, Johannsen, Moray, 1990]. The high complexity of the plant and the vague definition of the subtasks of the human supervisor as mentioned above may be of crucial significance. It is therefore that some special attention is focussed on the phenomenon of complexity [Stassen, 1992], before one is able to touch again the evaluation and validation of supervisory control behaviour.

In a recent article, it was stated that complexity is directly related to the combination of four factors [Tolsma, 1991]: great numbers, diversity, coupling, and interaction. This statement is difficult to defend; with a system theoretic apoproach, one might come to the following analysis. The factor of great numbers deals with the number of functions a system satisfies, whereas the factor of diversity may be interpreted in two different ways: either it means the different functions, or it means flexibility. Finally, the factors of coupling and interaction are synonymous with static and dynamic interaction. Hence, one can argue that complexity is mainly dependent on two factors: the number of functions and the interaction, and the design of a system is the optimisation of a criterion where complexity and flexibility are weighted.

By analogy with the well-known Richter-scale for earthquakes, one can define a scale from 0 until 7, describing the degree or intensity of complexity, whereby complexity is assumed to be dependent on at least two factors. Therefore, one defines lines where the complexity is constant, in the surface described by the coordinate system of degree of interaction over number of functions. These lines are called the Iso Complexity Curves, the ICCs. In Fig. 1, seven ICCs are proposed; in the left lower corner, the 0-ICC is drawn, in the right upper corner, the 7-ICC. It will be suggested that this classification of complex systems can be taken as a basis for developing a methodology to standardise evaluation and validation studies.

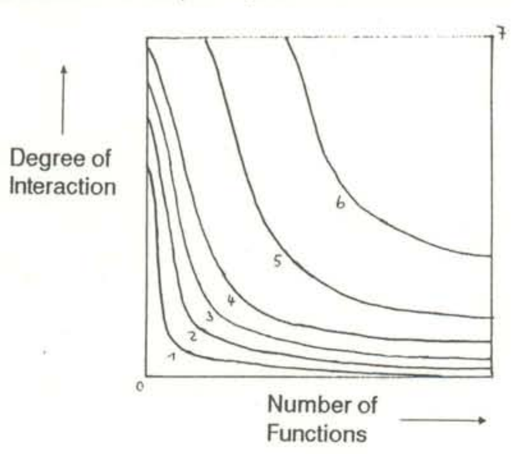

Fig. 1. Complexity defined as depending on the numbers of functions and the interaction. In the figure, the Iso Complexity Curves are indicated from 0 to 7. (after Stassen, 1992).

2. MODELLING HUMAN PERFORMANCE AND MENTAL WORKLOAD

The basic problem in modelling human performance and mental workload is to conceptualise a theory that allows one to smoothly and consistently move from the characteristics of the human to those of the system (the machine). While human and machine have essentially different characteristics (and there is no implication that we need machine-like models of humans) we should be able to describe or model those in a consistent analytical framework. Many of the mathematical formalisms that we have are well-suited to the description of machines and machine behaviour, but are not well-suited to the description of human behaviour.

Nevertheless, it can be stated that, with regard to human performance models, the goal of conceptualising such a theory has been achieved in manual control to a certain extent [McRuer, Jex, 1967; Kleinman, Baron, Levison, 1971; Stassen et al., 1990]. However, the mathematical formalisms for describing human supervisory control behaviour are still far away from what is desired; not any human performance model, mathematical or verbal, is able to fit human supervisory control behaviour, even not for just one of the six sub-tasks as mentioned in section 1. One of the major reasons may be the fact that all human performance modelling is based on the exact knowledge of the system dynamics, on well-defined tasks, and on knowledge of the statistics of the disturbances [Kalman, Bucy, 1961; Conant, Ashby, 1970; Francis, Wonham, 1975]. However, to what extent are these presumptions or hypotheses correct? In fact, one may even question whether it is at all possible to describe human supervisory control behaviour by general and accurate models [Stassen et al., 1990]. The large amount of models which has been reported for the six subtasks, and which are based on control and identification theory, detection and queueing theory, fuzzy set theory, expert and knowledge based systems, and artificial intelligence concepts, obviously show that no unique solution will be found.

Another view which supports what just has been argued, is based on the three-level concept of human cognitive behaviour [Rasmussen, 1983, 1986], where a distinction was made between a target-oriented Skill-Based Behaviour, SBB, a procedure oriented Rule-Based Behaviour, RBB, and a goal-controlled Knowledge-Based Behaviour, KBB. This qualitative model can be used in order to classify human operator tasks. It is widely accepted that manual control tasks and intervention tasks in stationary process conditions mainly lead to SBB, whereas monitoring, interpreting, and teaching a plant in stationary as well as in non-stationary conditions are most often RBB. Fault management and planning are not easily to be classified [Johannsen, 1988]. They require not only knowledge of the tasks to be performed, but also appeal to the creativity and intelligence of the human operator, hence, they lead to KBB. The Table 1 shows that different subtasks are performed at different cognitive levels and, as a consequence, simple models as validated in manual control certainly cannot be expected to be developed for supervisory control.Another aspect that complicates human performance modelling is the often extremely vague definition of tasks, a situation where the human´s creativity is explicitly required. This yields some very contradictory and intriguing statements, i. e.:

- If human creativity can be modelled, one can no longer speak about creativity; in fact one might say

Table 1. The relation between human behaviour and human operator tasks. The number of * indicates the significance of the relation (Stassen, Johannsen, Moray, (1990).

Human Behaviour \ Human Operator Tasks	Manual Control	Supervisory Control			
		Intervention	Interpreting Monitoring	Teaching	Fault Manag. Planning
SBB	* *	* *	*	*	*
RBB	*	*	* *	* *	*
KBB			*		* *

that the cognitive level of KBB is shifted to that of RBB.

- A good and practical system design should be robust for errors, however, one hopes for errors in order to stimulate human creativity.

A design is always the result of some kind of optimisation according to a more or less well-defined criterion, in this case a criterion where performance of human and system are weighted with the costs, i. e. mental workload. Unfortunately, the state of the art in mental workload modelling is even worse than that in performance modelling. Since Moray organised a workshop on mental workload, theory and applications in 1978 [Moray, 1979], a lot of work has been performed, but a profound theory is still not developed [Hart, 1987; Stassen et al., 1990]. The only goal achieved at this moment is a number of applicable and rather consistent measuring methodologies [Wickens, 1984; Hart, Wickens, 1990]. New critical reviews of workload research may be helpful but will not solve the problem. It is necessary to derive a conceptual model of mental workload on the basis of the integration of all existing material. The performance-workload-reliability-satisfaction relationships need to be better clarified within this conceptual model context. In addition, the question to what extent the internal representation, i. e. the knowledge available to the operator, plays a role in mental workload and also in performance is quite important. The whole issue is of high practical use for evaluating alternative man-machine system designs, particularly also those with computer-aided decision support.

From the literature, Table 2 can be reconstructed [Hart, 1987]. The table gives a global view on the state of the art in available human performance models and mental workload measurement techniques.

Table 2. Models for human performance and mental workload, as a function of the process control mode.
SBB = Skill-Based Behaviour; RBB = Rule-Based Behaviour; KBB = Knowledge-Based Behaviour.
+ = available; o = to a certain extent available; - = not available.

Process Control Mode	Perform. Level	Models Available	
		Perform.	Mental Workload
Manual Control	SBB	+	+
Stationary Supervisory Control	SBB RBB KBB	+ o -	o - -
Non-Stationary Supervisory Control	RBB KBB	o -	- -

3. TASK ALLOCATION AND DECISION SUPPORT

3.1 Human-Centred Perspective of Cooperative Problem Solving and Integrated Automation with Embedded Decision Support

Considering the six subtasks of the human supervisor, one may argue that the most important tasks are fault management and planning. In particular for these tasks, creativity of the human supervisor is required or, in terms of Rasmussens's three level model, KBB occurs. This yields that there is a need to support the human supervisor not only at the SBB- and RBB-levels but also at the KBB-level; see Fig. 2.

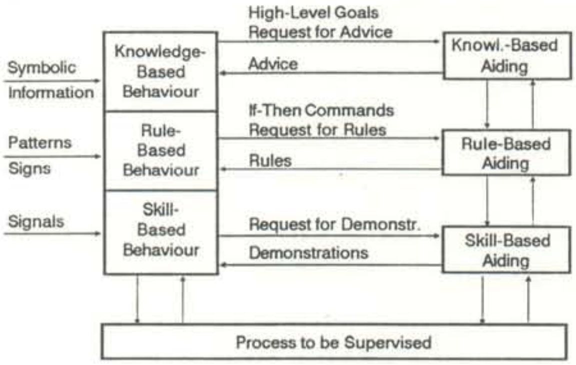

Fig. 2. Decision support systems classified according to the three-level model of Rasmussen (after Sheridan, 1987).

All kinds of decision support systems, including expert systems and knowledge-based systems, have been proposed and developed. It is amasing to see how much effort has been put into the design of those systems, and how little time was spent for their evaluation and validation. Several factors can be raised as possible causes. To start with, scientists and in particular computer scientists, are designers of tools and systems; it is their joy forever to create new systems. Probably, and hopefully, this attitude will change at the moment one realises that their products are not used the way it was expected. Often, these decision support systems degrade the human to someone who has to supply missing data or knowledge, and has finally to accept one problem solution or may be allowed to select among a few alternatives.

A much more prominent problem is the user-machine problem. As said before, the human supervisor needs to possess a correct internal representation of the process to be supervised, of the tasks to be performed, and of the disturbance statistics. In analogy, the designer of the decision support system needs to know how the user will use such a system, hence, the designer of the decision support system needs to build up an internal

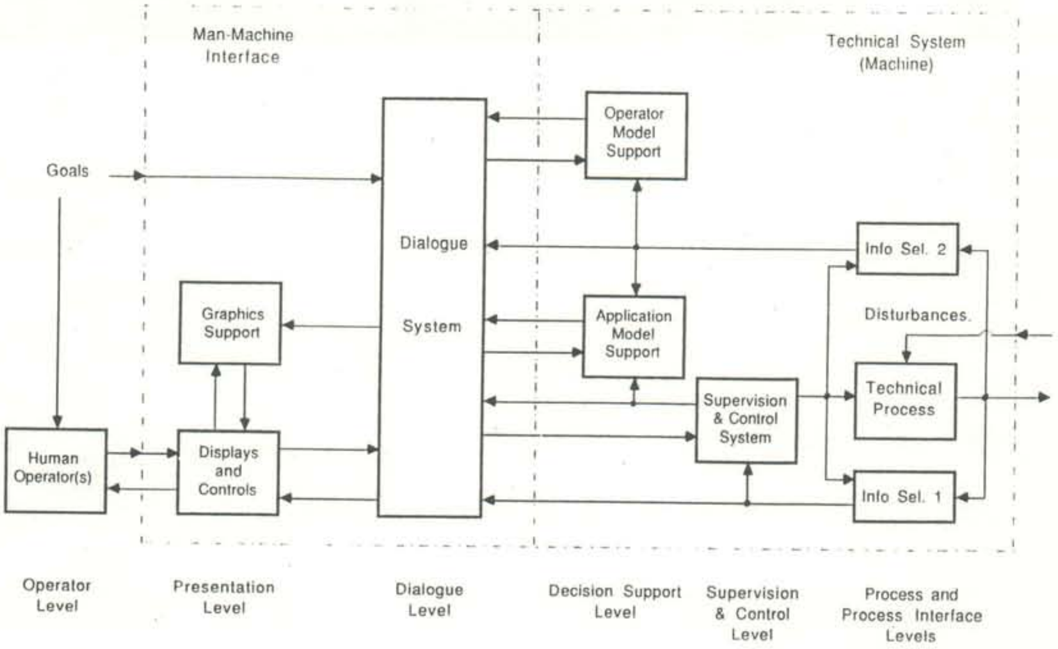

Fig. 3. Extended Operator (User) Interface Management System structure for dynamic technical systems (after Johannsen, 1992).

representation of the behaviour of the user. This aspect is often forgotten or neglected; honestly, it should be noted that this problem is extremely difficult to handle, and solutions are nowadays still not available. Another factor is the evaluation and validation of decision support systems. The fact that this activity is very time-consuming, where a general approach is not available, often leads to not doing it at all [Van Daalen, 1992]. Later, in section 6, some more attention will be paid to this important aspect.

The function and task allocations in complex man-machine systems need to consider different behavioural levels and information processing phases of human and automatic controlling and problem solving [Johannsen, 1991, 1992]. Within an extended Operator (User) Interface Management System architecture, the functionalities of the technical system include those of the technical process, the traditional automation (computer supervision & control), and the computer support (decision support based on application and operator modelling). This architecture ist shown in Fig. 3 and, with more detailed hierarchical levels, in Fig. 4.

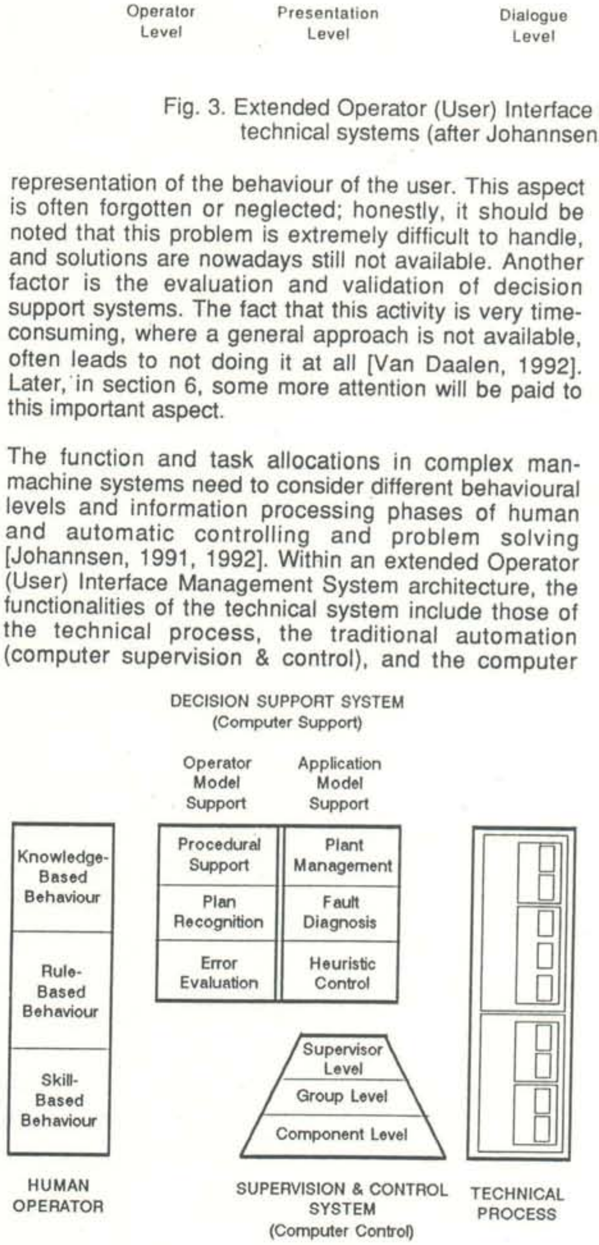

Fig. 4. Relationship between human operator, decision support system, supervision & control system, and technical process (from Johannsen, 1992).

The term integrated automation is also used for this concept. The man-machine interface is left out in Fig. 4 for reasons of simplicity; it is outlined with its presentation and dialogue levels in Fig. 3 and will be discussed in section 4 of this paper.

The function and task allocations have to be achieved under consideration of all the possibilities available with the capabilities of the human operator(s), the different decision support systems, and the supervision & control system. Starting from a human-centred perspective, a cooperative problem solving approach is very much needed. The cooperation is meant between human and machine problem solvers. In any case, the main responsibility lies with the human problem solver. Thus, several types of cooperation with different degrees of machine subordination can be thought of. Examples as shown in Fig. 4 are the application-oriented decision support systems for fault diagnosis, particularly those which combine human and computer reasoning processes based on test procedures, value histories, and transition networks [Borndorff-Eccarius, 1990]. Other examples which are more operator-oriented decision support systems were developed as operator´s associates for procedural support and intent recognition [Rubin at al., 1988; Sundström, 1991; Johannsen, 1992]. In order to improve such cooperative systems, the knowledge structures and the problem solving strategies of humans as well as their cognitive biases and deficits need to be better understood for a number of different application domains. The difficult and time-consuming techniques of knowledge elicitation in cognitive task analyses have to be further elaborated [Johannsen, Alty, 1991] and have to be applied in order to serve the requirements of cognitive modelling of the human problem solver. The conceptual models, such as that of Rasmussen [1983, 1986], have to be further elaborated, extended and/or modified, and at least partially validated. The final objective can be a form of dynamic task allocation for cooperative problem solving where the machine serves the human by knowledge enhancement and by interactive procedural support.

New approaches exist for evaluating human errors on the key-stroke level, for checking the consistencies of input sequences, and for intent or plan recognition [Heßler, 1989; Johannsen, 1992]. These approaches can be based on models of correct task execution. For further development, it will be important to introduce the natural fuzziness of task execution into such models. Furthermore, the question exists whether the recognition of human errors on higher cognitive levels will be at all possible, or whether we reach limits of our understanding. Understanding human error as well as the limits of our understanding is of major practical use with respect to our responsibility for the control of complex man-machine systems. It contributes also to the cooperative problem solving approach mentioned above.

The introduction of systems that learn or, at least, have their knowledge base change with time creates further problems. Consider the case that several identical decision support systems — each with the same knowledge base — are installed in different departments of an organisation. In the beginning, there is indirect coordination among the decision support systems. But as time passes and the knowledge base evolves differently in the different systems, the indirect coordination will disappear with the possibility now present that conflicts and instabilities may be created within the organisation We need a theoretical framework that allows us to allocate resources — human and machine resources — dynamically to tasks while maintaining information consistency and indirect coordination. To develop such a theory we need to understand both the human aspects and the machine aspects and merge them together — not the one being an afterthought of the other. Such a theory should apply equally well to systems consisting of a single human with a single machine and to teams of humans with distributed machine systems.

3.2 Distributed Decision Making in Teams of Humans with Computer Support

A more complex problem arises when computer support, in the form of a decision support system (DSS), is introduced in an organisation. Let the organisation represent a team and let the task allocation be such that the team engages in distributed decision making. This means that the decision problem has been decomposed into individual subproblems, each assigned to a different organisation member. However, these subproblems must be solved in a coordinated manner to produce the organisational response. The decision support system may contain a number of features: it can contain a centralised or distributed data base that the individual decision makers can access; it probably includes a communication system that allows the different team members to interact — to communicate directly and to exchange data and results; and it may also include decision aids that can support the tasks of individual members. The presence of the decision support system raises two design problems, both at the theoretical and the practical level.

The first problem, and the most obvious one, is the interaction of each individual team member with the decision support system itself, seen as a decision aid. The original task, allocated to that particular team member, will now be shared with the machine. This is a classic allocation problem: what does the human do and what does the machine do? The result of this allocation leads to the definition of the Human-Computer Interaction (HCI) problem. Note that designing the HCI can follow general theoretical principles based on theories of cognitive processing and on human factors research, but that the actual design is very dependent on the answer to the allocation problem between the human and the machine. Embedded in this well defined problem is a more subtle one: the manner in which the decision aid is used. While there is a whole spectrum of interactions, it is convenient to describe three distinct modes. Clearly, the decision maker may ignore the decision aid — he or she may not query the data bases or not use the information it provides. While this is an extreme case, it is a definite possibility, especially if the support system has been designed in such a manner that the task can be performed without the use of the decision aiding capabilities of the support system. The other extreme occurs when the interaction between the human and the machine follows prescribed steps — the operational concept requires that the human interacts with the machine in order for the next step in the process to be enabled. The machine is not just supporting the decision maker, it carries out some parts of the decision making task itself. Some forms of this interaction may be labelled supervisory control — the decision aid acts as a controller and the human decision maker intervenes by issuing commands to the aid or resetting parameters, as appropriate. The third mode is, of course, the more interesting one. The decision aid plays a consulting role: the decision maker consults the aid and then he may or may not use the information or recommendations provided as to the preferred course of action.

The three modes are shown schematically in Fig. 5. The bold lines indicate the flow of task related activities. In Fig. 5 (a) the decision maker carries out his task without interacting with the aid or without availing himself of the services of the decision support system (as indicated by the dashed lines). In Fig. 5 (b) one of the possible variants between an integrated operation between a human and a machine is shown. The task is received by the decision maker, he carries part of the task, then control is transferred to the machine by the human. The machine does its part of the task and transfers information and control to the human for completion of the task. The dashed line between the two-part model of the decision maker indicates that the human cannot bypass the machine and carry out the task without it.

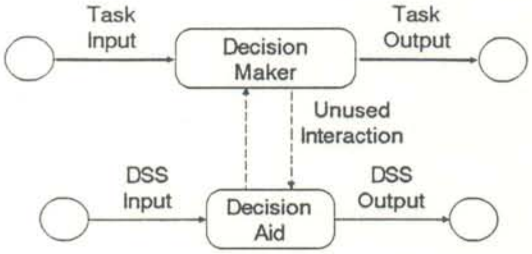

Fig. 5 (a). Unaided decision maker.

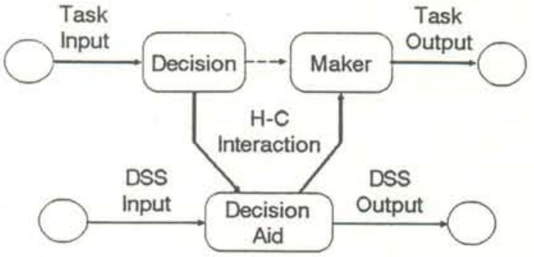

Fig. 5 (b). Integrated human-computer interaction.

The third Fig. 5 (c) shows the case that the human-computer interaction is optional: the decision maker chooses to query the decision aid (or consult it) and then uses or ignores the output of the aid. This gives more flexibility to the decision maker but it also increases his mental workload: in addition to processing the task itself, he now has to make additional decisions regarding the proper use of the decision aid and of the results it produces. This phenomenon is called meta-

HUMAN ← computer

Increase in Automation Intelligence

Analysis	Decision Process	Execution
HUMAN SUPERVISOR GENERATES ALTERNATIVES	HUMAN SUPERVISOR TAKES DECISION	HUMAN SUPERVISOR EXECUTES
computer generates alternatives	HUMAN SUPERVISOR TAKES DECISION	HUMAN SUPERVISOR EXECUTES
computer generates and selects alternatives	HUMAN SUPERVISOR TAKES DECISION	HUMAN SUPERVISOR EXECUTES
computer generates and adv. best alternatives	HUMAN SUPERVISOR TAKES DECISION	HUMAN SUPERVISOR EXECUTES
computer generates and adv. best alternatives	HUMAN SUPERVISOR TAKES DECISION	computer executes, if HUMAN SUPERVISOR OK
computer generates alternatives	computer takes decision	computer executes, if HUMAN SUPERVISOR GENERATES NO VETO
computer generates alternatives	computer takes decision	computer executes, but must inform HUMAN SUPERVISOR
computer generates alternatives	computer takes decision	computer executes, informs HUMAN SUPERVISOR IF HUMAN SUPERVISOR ASKS
computer generates alternatives	computer takes decision	computer executes, informs HUMAN SUPERVISOR, if computer agrees
computer generates alternatives	computer takes decision	computer executes

Fig. 6. Task allocation between human (denoted by capital letters) and computer (after Sheridan, 1980).

The present way of designing man-machine interfaces, supervision and control systems, decision support systems, and/or control rooms are as follows. The industrial management defines the product specifications, on the basis of which the process engineer develops the process. Then, control engineers design the control and safety systems, hardware as well as software. and they often also determine which information will be displayed by the interfaces in the control room, and which variables can be controlled by the human supervisor. Moreover, they often indicate the lay-out of the control room and its man-machine interfaces. Sometimes, the human factors, ergonomics, and man-machine system disciplines can contribute to the design at this phase. However in many cases, no influence of these experts is requested at all. Thus, in the overall design process, ergonomists or man-machine-system specialists usually have to cope with a man-machine interface already fully determined by the control engineer, in this way leaving open only questions concerning the definition of supervisory tasks, the recruitment, training and selection of potential operators, and the classical human factors aspects of displays and controls. This procedure will lead to conflicts in the allocation of tasks between operator and machine, among others because the man-machine systems discipline is called in at a too late phase of the design process of the control room. In fact, the design process should be achieved just the other way around, in starting with a correct allocation of the tasks to be performed. This fact, combined with the consequences of the ongoing automation, the vital role of the human in supervision of the plant and the necessary multi-disciplinary approach, have asked for the development of man-machine guidelines.

The purpose of these guidelines is not to replace the specialised knowledge of the designer, nor to come to a standardisation which often delays progress in new developments of hardware and software. However, it is just to point out the need for a particular multi-disciplinary expertise at all levels of the decision making in the design process [Stassen, 1984; Gilmore et al., 1989]. In this way, for example, the EWICS-guidelines were developed by the members of the European Workshop on Industrial Computer Systems during the period from 1981 until 1986 [Scanlon, 1981; Wirstad, 1982; Stassen et al., 1986]. Of course, these and other guidelines may be helpful, but they are certainly not an adequate answer to the task allocation problem. What is needed is a methodology for building up models to describe the allocation of tasks.

A methodology, full of expectations, is probably the one which is based on coloured Petri nets [Boettcher and Levis, 1982; Levis et al., 1992]. With this method, tasks, task interactions, and organisational structures can quantitatively be described [Levis, 1988]. In addition, the effectiveness and the safety of systems supervised by a human supervisor can be estimated. The strong point of the method is that system and human behaviour are modelled with just one method in the same way.

6. EVALUATION AND EXPERIMENTAL VALIDATION

6.1 Laboratory and Field Evaluations

There is a very limited experience in the evaluation and validation of man-machine interfaces and decision support systems in an operational environment. Extensive laboratory evaluations will have to precede evaluations of systems in the real world. In particular, it may be helpful to survey the experiences in the field of medical diagnosis with reference to the use of expert and knowledge-based systems [Van Daalen, 1992]. The evaluation of man-machine interfaces and all kinds of decision support systems is cursed with problems, many of which cannot easily be solved. Direct practical problems are the large amount of variables, the wide range of these variables, the typical human cognitive properties such as memory and adaptivity, the discrete and abrupt changes in behaviour, the very seldomly occuring disturbances, and the time-consuming processes of carrying out evaluations or of even running more formal experiments. All these problems yield that rather seldomly evaluations and validations of newly designed man-machine interfaces and decision support systems are performed at all — even more seldomly they are performed in a rigorous way.

However, evaluation studies should be a continuous process which has to be carried out in parallel with the development of any man-machine system and, particularly, of its man-machine interface and all technical subsystems. In the beginning, evaluation will be directed towards obtaining information for the improvement of the system; later on, an evaluation will be aimed at investigating whether the system satisfies the design objectives. It also implies that the evaluation will move from informal studies to formal investigations. The informal studies include expert evaluations in cognitive task analyses, knowledge elicitation, and participative system prototyping [Johannsen and Alty, decision making. The three types of interactions have been studied by Weingaertner (1989), Grevet (1988) and Perdu (1991).

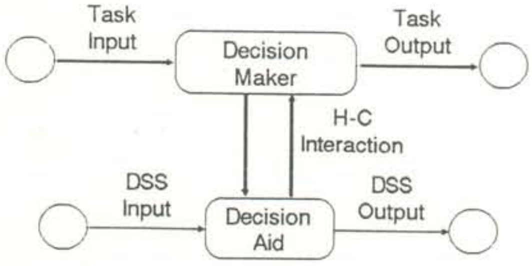

Fig. 5 (c). Optional human-computer interaction.

The second problem has to do with the interactions among the decision makers. There are three types of interactions that can be identified in distributed decision making. Each one of them imposes different information exchange and communications requirements that the support system must meet. The first type is the exchange of information regarding the state of the system, as seen by each decision maker. This can be called information sharing and helps indirectly in coordinating the distributed decision making by broadening the situation assessment of each decision maker: it reduces the differences in their estimates of the system state. Note that in a distributed system, each decision maker may be seeing only a few of the state variables and some aggregates of the rest of the variables. The second type is the exchange of results or results sharing. In this case, a decision maker communicates to others what he is going to do (or what decision he has made) rather than describing them what he perceives the situation to be. Note that the advantage of this approach is that it reduces the communication requirements and corresponds to communicating the individual control actions to the members rather than their part of the state. This approach provides a more direct means of coordinating, provided the various decision makers share common mental models of the system's operation so that they can interpret the control actions correctly. The reduction in communication is counterbalanced by an increase in the cognitive processing — the interpretation of the controls. In very broad terms, it can be interpreted as inferring from the control what the state was that led to that decision. The third type of exchange is a direct one in which one decision maker issues orders or commands to others. In most distributed decision making environments, there is an embedded hierarchical structure — a shift supervisor, a controller, a foreman, or a manager. These are special communications that restrict the options of the subordinates; they reduce the cognitive load of the subordinates by reducing the number of alternatives (sometimes down to a single alternative as is the case of a direct command) and by reducing the mental workload associated with situation assessment. It may increase, however, the workload of the supervisor, mitigating the advantages of distributed decision making. Computer support in an organisation makes possible all these types of interactions that support coordination. This is a design problem that cannot be left to chance given a task allocation solution. This type of problem is being investigated both theoretically and experimentally under the rubric of coordination in decision making organisations [Lu and Levis, 1991; Wang et al. 1991].

4. MAN-MACHINE INTERFACES

A key problem in man-machine systems is the determination of the boundary between the human and the machine and the manipulation of the boundary — the interface — to "match impedance". The questions of where that boundary should be and whether the boundary should be fixed or flexible with respect to a wide variety of tasks or even changing with time, contribute to the issues of task allocations and decision support systems (as described above). Additionally, the issues of the organisation of the information flow across the boundary and the form of the information presentation are very important. The investigations of the man-machine interfaces in the narrower sense have to deal with these problems. Following the UIMS (User Interface Management System) concept, dialogue issues can be separated from presentation issues [Alty, Johannsen, 1989; Johannsen, 1992]. The presentation issues are concerned with displays and controls as well as with knowledge-based graphics support. The dialogue system may also contain knowledge-based modules (e. g., so-called dialogue assistants) which relate to the different subsystems of the machine — including a number of different decision support systems — and deal with local knowledge about these subsystems for observing and controlling the dialogue information flow, and for picking up loose ends of dialogue in case of priority interrupts.

A lot of basic research results exists in the literature [e. g., Gilmore et al., 1989; Diaper et al., 1990; Fejes et al., 1992]. Nevertheless, there is still a need of practical guidelines for the design of information presentation in control rooms, particularly when hundreds of pictures are needed by the operators. This aspect will be taken up again in section 5. One question is: what is the appropriate mixture between parallel and serial information presentation? This question is mainly of concern for the organisation of the graphical output of the technical system. However, it may also be of interest for the organisation of inputs into the technical system, particularly when the inputs are also graphically supported, e. g., as with touch-screens [Hartz, Borys, 1990].

5. DESIGN PROBLEMS

A thorough systems approach in design is necessary which suggests a goal-oriented top-down procedure supported by bottom-up means [Gilmore et al., 1989; Rouse, 1991]. The design of man-machine interfaces and of decision support systems requires at least a well-defined task. Then, on the basis of such a task description, one may design interfaces and support systems by taking into account, on the one hand, the dynamics of the system to be supervised and, on the other, the capabilities and limitations of the human supervisor. Hence, the underlying problem is again that of a responsible allocation of tasks between man and machine, as has been elaborated already in section 3. This task allocation is dependent on the amount of automation intelligence applied [Sheridan, 1980] and can be of help at all three cognitive levels which are shown in Fig. 2. A taxonomy of the introduction of automation intelligence in the design of a controlled process is shown in Fig. 6; it elucidates that the choice of the degree of automation intelligence is to be based on the cognitive processes the human supervisor is able to achieve.

For a long time, it was believed that the automation level could be chosen a-priori by the designer. However, in the practice of the real world, it is experienced that this approach fails; it is too simple. The needs for help which have to be supplied by the designer may differ among the human operators and the expected process control modes, and they may vary in time. Therefore, the designer cannot decide and just make a choice. At least, the system to be developed should be flexible, and probably it is even necessary to make the system adaptive to the circumstances.

1991]. However, some of these techniques have been developed to a fairly high degree of formality during the last years. The formal evaluation of knowledge-based systems in field studies will involve the validation, whereby it should be shown to a satisfactory degree that the behaviour of the system is correct with respect to the specifications prescribed for the system [Shwe et al., 1989]. Furthermore, the user interaction should be investigated, and the performance of a system in a laboratory environment should be evaluated, where safety, accuracy, reliability and transferability are important. Here, it should be noted that formal field evaluations should only be carried out after demonstrating superior performance in a laboratory experiment. Only a few systems have reached the level of maturity which is required to justify a field evaluation. Examples, in the medical field, which have undergone field evaluations may be found in the literature [Adams, 1986; Sutton, 1989; Murray, 1990].

Field evaluations should involve investigations of the efficacy of the system in the target environment by measuring the impact of system use on the quality of the user´s decisions and the impact of the system on the results of the user´s task performance. Furthermore, the human-machine interaction is of utmost importance and should be evaluated also. It will involve assessments of the acceptibility and the usability of the system and of the quality of the human-computer interface. Cost-benefit analyses should be carried out, and the impact on the organisation and the social environment as well as legal and ethical aspects should be assessed.

Just to give an example, in the evaluation of the efficacy of a decision support system, the following classification can be used as a framework of the evaluation: Selection of the goals for evaluation; the experimental setup, containing the choice of the experimenal unit, the specification of the control group, the selection of the test input, the selection of the way to enter the test data, the specification of a standard of performance, and the specification of the variables to be measured; the analysis of the results; and finally, the bias and the confounding variables. Altogether, it is clear that an evaluation study is a large and very time-consuming activity. It is, therefore, obvious that a standard methodology has to be developed in order

- to decrease the evaluation time and effort;
- to compare results obtained from different processes, process control modes, and process circumstances, hence from processes with different degrees of complexity; and
- to compare results obtained at different locations and laboratories.

In order to come to such a standard experimental set-up, one may consider the concept of the Iso Complexity Curves. At the moment that different processes — different in terms of the number of functions to be supervised and of the degree of interaction — can be standardised by the Iso Complexity Curves mentioned earlier, one could develop a methodology to measure performance as a function of the Iso Complexity Curve value. Hence, standard processes, such as the Generic Power Plant or the William´s plant for the chemical industry, can be categorised by the Iso Complexity Curve number and, thus, by a certain performance index. To what extent this philosophy can be extended to mental workload studies is difficult to be estimated but, at least, it should be given a trial.

In those cases where the degree of complexity is very high, measures can be achieved in order to decrease the degree of complexity experienced, such as the reduction of the number of components [Tolsma, 1991], cancelling out the interactions by decoupling [Van der Veldt and Van den Boomgaard, 1985], presenting information about the interaction by means of predictive displays [Veldhuijzen and Stassen, 1977; Johannsen und Govindaraj, 1980], or by using artificial intelligence concepts as done in integrated automation or plant-wide control [Johannsen, 1991, 1992].

It is believed that by simulation for each Iso Complexity Curve, performance and mental workload indices can be found and, thus, a more or less standardised procedure can be achieved. However, there are many very practical problems in executing this type of research; to mention the most important ones:

- The facilities to simulate a control room, a process to be supervised, a series of realistic disturbances, and the tasks to be achieved are rather expensive, in terms of hardware and software. In addition, it requires a very good feedback from industry.
- The training of potential subjects is very time-consuming; often, one cannot replace the actual human operators by just students.
- In particular, human performance on very seldomly occuring disturbances, as it may happen in nuclear power plants, is extremely difficult to be estimated. Note that time scaling is mostly not allowed at all.
- The practical definitions of performance and of mental workload indices are difficult to be achieved.

6.2 Experimental Design and Validation

Experiments involving several human decision makers and computer simulations are generally complex and difficult to design and control. One of the difficulties is the large number of parameters involved. A second difficulty is determining which parameters should be held fixed, and which ones should be varied and over what range. A third problem is that the participation of human decision makers in the experiment precludes the execution of a large number of trials. While there is a strong tradition of experiments with single decision makers, no useful guidelines for experiments with decision making teams are available. In most cases, if the task is complex, the organisation is a simple one, while if the organisational structure is complex, the task is very simple. This is not a satisfactory situation, especially when the real problems today involve small decision making teams employing complex procedures to monitor and control complex engineering systems. Examples of problems include air traffic control, the control of energy systems (nuclear power plant control), or the control of a highly automated manufacturing plants.

In order to design a controllable experiment in a complicated environment, a model is necessary for determining appropriate variables which ought to be controlled or measured. In the physical sciences and in engineering, procedures have been developed over the years for using models to design experiments. For example, to address the problem of many parameters and the problem of physical scale, dimensional analysis has been developed and is routinely used in mechanical and aeronautical engineering (Hunsacker and Rightmire, 1947). This well established technique from the physical sciences has been extended to include the cognitive aspects of the distributed decision making environment (Jin and Levis,1992).

A dimension is the measure which expresses a physical variable qualitatively. Fundamental dimensions are the primary dimensions which characterises all variables in a physical system. For example, length, mass, and time are fundamental dimensions in mechanical systems. A dimension such as length per time is a secondary or derived dimension. If the dimension of a physical variable cannot be expressed by the dimensions of others in the same equation, then this variable is dimensionally independent.

The foundation of dimensional analysis is the Principle of Dimensional Homogeneity, which states that if an equation truly describes a physical phenomenon, it must be dimensionally homogeneous, i.e., each of its additive terms should have the same dimension. The basic theorem of dimensional analysis is the π theorem, also called Buckingham's theorem which states that if a physical process is described by a dimensionally homogeneous relation involving n dimensional variables, such as

$$x_1 = f(x_2, x_3, \ldots, x_n) \qquad (1)$$

then there exists an equivalent relation involving (n-k) dimensionless variables, such as

$$\pi_1 = F(\pi_2, \pi_3, \ldots \pi_{n-k}) \qquad (2)$$

where k is usually equal to, but never greater than, the number of fundamental dimensions involved in the x's. It is clear from comparing Eqs. (1) and (2) that the number of independent variables is reduced by k, where k is the maximum number of dimensionally independent variables in the relation. The π theorem provides a more efficient way to organise and manage the variables in a specific problem and guarantees a reduction of the number of independent variables in a relation.

To apply dimensional analysis to decisionmaking organisations, the fundamental dimensions of the variables that describe their behaviour must be determined. A system of three dimensions is shown in Table 3 that is considered adequate for modeling cognitive workload and bounded rationality. The approach was applied first to a 1988 experiment [Louvet et al., 1988] to demonstrate the application of dimensional analysis to the experimental investigation of bounded rationality. The purpose of the single-person experiment was to investigate the bounded rationality constraint. The experimental task was to select the smallest ratio from a sequence of comparisons of ratios consisting of two two-digit integers. Two ratios were presented to a subject at each time. The subject needed to decide the smaller one and to compare it with the next incoming ratio until all ratios were compared and the smallest one was found. The controlled variable (or manipulated variable) was the amount of time allowed to perform the task. The measured variable was the accuracy of the response, i.e., whether the correct ratio was selected.

Table 3. Dimensions for Cognitive Problems

Dimension	Symbol	Unit
Time	T	sec
Information (uncertainty)	I	bit
Task	S	symbol

The controlled variables were the number of comparisons in a sequence, denoted by N, and the allotted time to do the task, denoted by T_W. For each value of N, T_W took m values with constant increment. The performance was considered to be accurate or correct if the sequence of comparisons was completed and if the smallest ratio selected was correct.

The hypothesis to be proved in that experiment was that there exists a maximum processing rate for human decision makers. When the allotted time is decreased, there will be a time beyond which the time spent doing the task will have to be reduced, if the execution of the task is to be completed. This will result in an increase in the information processing rate F, if the workload is kept constant. However, the bounded rationality constraint limits the increase of F to a maximum value F_{max}. When the allotted time for a particular task becomes so small that the processing rate reaches F_{max}, further decrease of the allotted time will cause performance to degrade. The performance drops either because all comparisons were not made or because errors were made. It was hypothesised that the bounded rationality constraint F_{max} is constant for each individual decision maker, but varies from individual to individual. The bounded rationality constraint can be expressed as

$$F \leq F_{max} = G / T_W^{*} \qquad (3)$$

where T_W^{*} is the minimum allotted time before performance degrades significantly. G and T_W^{*} vary for different tasks, but F_{max} should remain constant for a decision maker, no matter what kind of tasks he does. Therefore, significant degradation of performance indicates that the allotted time approaches T_W^{*}. Observation of this degradation during the experiment allows the determination of the time threshold and, therefore, the maximum processing rate, provided the workload associated with a specific task can be estimated or calculated.

The application of dimensional analysis reduces the complexity of the equations and facilitates experimental design and analysis. Properly designed experiments using dimensional analysis provide similitude of experimental condition for different combinations of dimensional variables which result in the same value of p´s. Similitude reduces the number of trials needed. This is a major advantage when the physical (dimensional) experimental variables cannot be set at arbitrary values. This technique addresses all the problems stated earlier but one: the problem of selecting the ranges of variables to be changed during the experiment so that the behaviours of interest can be captures by a limited number of trials. This is a practical consideration given the difficulties associated with using many teams of trained decision makers over many trials. Model-driven experimental design is one useful approach to this problem.

6.3 Model-Driven Experimentation

The experimental design starts with the development of a model that represents the experiment. The model contains Models of the individual decision makers, the decision strategies that each team member has available, the protocols of interactions between team members and the task the team is to execute. The model also contains in an explicit form the experimental variables that are to be manipulated and the measured variables that are to be collected in the actual experiment. Finally, the model contains the data processing and analysis techniques that will be used in determining the validity of the hypotheses being investigated. In simple terms, the model simulates the experiment and generates pseudo-data. One key consideration in the above approach is the need for the assumptions embedded in the model to be consistent with those underlying the actual experiment. This is difficult to achieve in general, but it is essential. For example, human dicision makers may exhibit behaviour that is not included in the model (they may select strategies outside the range assumed in the model or they may use past experience — memory — while the model assumes memoryless operation).

Running a small-scale pilot experiment may be necessary at this stage to determine the ranges for certain time variables for which no theoretically derived quantitative estimate is available. For example, it may not be possible to predict for a particular cognitive task the minimum amount of time necessary to carry it out correctly. A separate single person experiment may be run for this type of task to obtain an estimate of the minimum time; this estimate is then used in the team model where members carry out similar cognitive tasks.

Simulations and analysis are then used to predict team performance for various values of the controlled variables. Specifically, the simulations may indicate for what combination of parameter values a discrete change in behaviour can occur. This information is used in the actual experiment by assuring that these sets of values are included in the experimental program. In the actual experiment, it is the dimensionless groups that are manipulated. This is very useful because the parameters that reflect human characteristics cannot be manipulated at will; however, the environmental parameters can be manipulated by the experimenter so that the dimensionless group takes the required set of values. The predictions from analysis and simulation results lead then to the formulation of quantitative hypotheses that can be tested experimentally.

This engineering-based methodology is feasible and practical and was shown to be applicable to the design of model-driven experiments in team decision making; it has actually led to the formulation of hypotheses and to the design of an experiment, and has guided the collection and analysis of data for proving or disproving the hypotheses [Jin and Levis, 1992]. A special class of organisations was considered — a team of well-trained decision makers repetitively executing a set of well-defined cognitive tasks under severe time pressure. The cognitive limitations of decision makers imposed a constraint on organisational performance. Performance, in this case, was assumed to depend mainly on the time available to perform a task and on the cognitive workload associated with the task. When the time available to perform a task is very short (time pressure is very high), decision makers are likely to make mistakes (human error) so that performance will be degraded.

The experimental results showed, as predicted, that the accuracy of the response decreases as the available time to do a task is reduced. The variation in performance is less between different teams than between different individual decision makers within a team, which means *that organisational performance is more predictable than individual performance.* It has also been found that degradation of accuracy as a function of available time is less abrupt for organisations than for individuals. *Interaction among decision makers in an organisation compensates for differences in individual performance characteristics.* These results are consistent with the predictions from the theoretical model. Furthermore, *the critical value of the ratio of response time to available time for doing a task is an observable measure of the bounded rationality constraint.* Therefore, this ratio, which is observable from simple experiments, can be used in development of future organisation designs as a key design parameter.

In this section, it has been shown that the use of computer simulation and analytical models, when combined with engineering techniques for large scale experimentation, provide a feasible approach for addressing the need for reliable and repeatable experimental data on the behaviour of team members executing complex tasks in the context of an engineering system, an environment in which team members interact with the system and with each other through man-machine interfaces.

7. CONCLUDING REMARK

This paper clearly shows that we face several unsolved problems in our multidisciplinary field of man-machine systems. Basically, the most severe ones are determined in some way by our limited understanding of the higher cognitive behaviour of humans. Of course, we need a lot of future research and good ideas to improve this situation.

However, we also outlined here the many facets of available knowledge. Maybe, the main statement which we can make is that all experts of our discipline should be courageous and strong enough for applying our know-how in real systems and for training designers and managers about it. If we hesitate because of our limited knowledge, other people will continue to build new technical systems with much less or even no knowledge about the man-machine relationship.

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