HUMAN FACTORS IN THE DESIGN PROCESS OF ADVANCED SUPERVISORY AND CONTROL SYSTEMS

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Summary

The design of control systems and human-machine interfaces in the field of complex and safety critical environments remains today an open issue, in spite of the high technological evolution of the last years. The increasing use of automation has improved efficiency, safety and easiness of operations but, at the same time, has complicated operator's situation awareness and has changed the nature of their possible operative errors. The PhD project described in this paper is an attempt to develop a methodological framework to support designers of control systems and human-machine interfaces, focusing in a particular way on the need of a deeply recursive approach related to the implementation of the systemic and human aspects in the design process of a human-machine system intended as a *Joint Cognitive System*. A validating case study has been performed, based of the full application of the framework on the control of the turbine/alternator system of a thermoelectric power plant in Northern Italy.

1. Introduction

The research project here below described, is concerned with a PhD activity performed over the period 1998-2001: this paper has the purpose of representing a final document descriptive of the related overall approaches and results. The activity has been developed in cooperation between the Department of Energetics of the Politecnico di Torino, the Joint Research Centre of the European Commission (Ispra site) and the Azienda Energetica Metropolitana of Torino.

Two issues have been at the basis of the choice of this subject. From one side, the wider and wider use of *automation* is an aspect highly characterising the modern technological society, with such an impact on the public opinion that there exists the feeling that also the minimal failure of some automatic control system could give rise to disastrous consequences [1]. From the other side, the frequent tendency to assign to the *human error* the role of ultimate cause of incidental sequences represents a not always correct and exhaustive (and too often voluntary superficial) inquiry process: Human Factors experts agree that an operative error has to be seldom considered as a simple cause, but has often to be seen as one of the links of a chain of causes/effects originating from design, organisational and management problems.

Therefore, this situation must be observed from a different and wider point of view: the technological development has actually improved the hardware and software components and the system configurations, but the reliability aspects related to human control have not been object of so much attention and of an adequate and contemporary development. As a consequence, the human element has become the relatively weakest issue in the modern and highly automated systems, and the deep understanding by the operators of the higher and higher complexity represents a fundamental step in the design of human-machine systems.

In this perspective, the research project described in this paper represents an attempt to develop a methodological framework to support designers of control systems and human-machine interfaces, by conveying modern theories of supervisory/cognitive control and human-centred design principles [2, 3]. A particular attention has been devoted to the need of a recursive approach related to the implementation of the systemic and human aspects in the design process of a human-machine system intended as a "Joint Cognitive System" [4].

The application to a real case has then been developed. A thermoelectric power plant has been selected in Northern Italy, where an overall upgrading program is going on. The case study has been focused on the control system and the related human-machine interfaces for the turbine-alternator group of the plant, with a twofold objective:

- to validate the methodological framework, helping to refine the selection methods of available techniques and the links between different phases;
- to give a critical review of the existing control and HMI system, and to propose design guidelines for possible improvements and modifications.

In the following, all the theoretical aspects of the research activity and the main results of the case study application will be described and discussed.

2. The proposed methodological framework

The theoretical core of the research activity has been the proposal of a methodological framework, intended to be a means offered to designers to exploit and apply available practical elements and most validated theoretical support. The approach is based on two fundamental assumptions, coming from cognitive systems engineering and cognitive ergonomics [4]:

- firstly, it is assumed that interactions between humans and automated control systems must be considered in terms of a "Joint Cognitive System";
- secondly, it is recognised that human behaviour (and consequently all the possible erroneous actions) is deeply influenced by the socio-technical context in which it develops.

The notion of *Joint Cognitive System* (JCS) mainly comes from the theories of supervisory control [5]. According to these theories the operator remains at the top of the system and can substitute the automated control system when a particular situation requires it: then, the machine essentially acts as an "intelligent assistant", whose role is to support operators in the control of physical processes. This notion requires that the *human* and the *machine* must be modelled in equivalent terms and that a highly integrated coupling of the two models is essential to describe and analyse the detail of the interaction. In addition, this standpoint is based on the premise that human cognition is an active process, that can be modified and influenced by operator's objectives and by the context and the situation: the description of the behaviour has to be seen from a global point of view and not in terms of a single human or systemic component.

The overall proposed framework is shown in figure 1. A detailed number of available instruments (methodologies and techniques) is supplied in order to allow the construction of:

- a *System Model*, with deep knowledge about the system from structural, functional and environmental point of view;
- a *Human Model*, with selection of the most suitable cognitive and human error model/simulation and corresponding taxonomy;

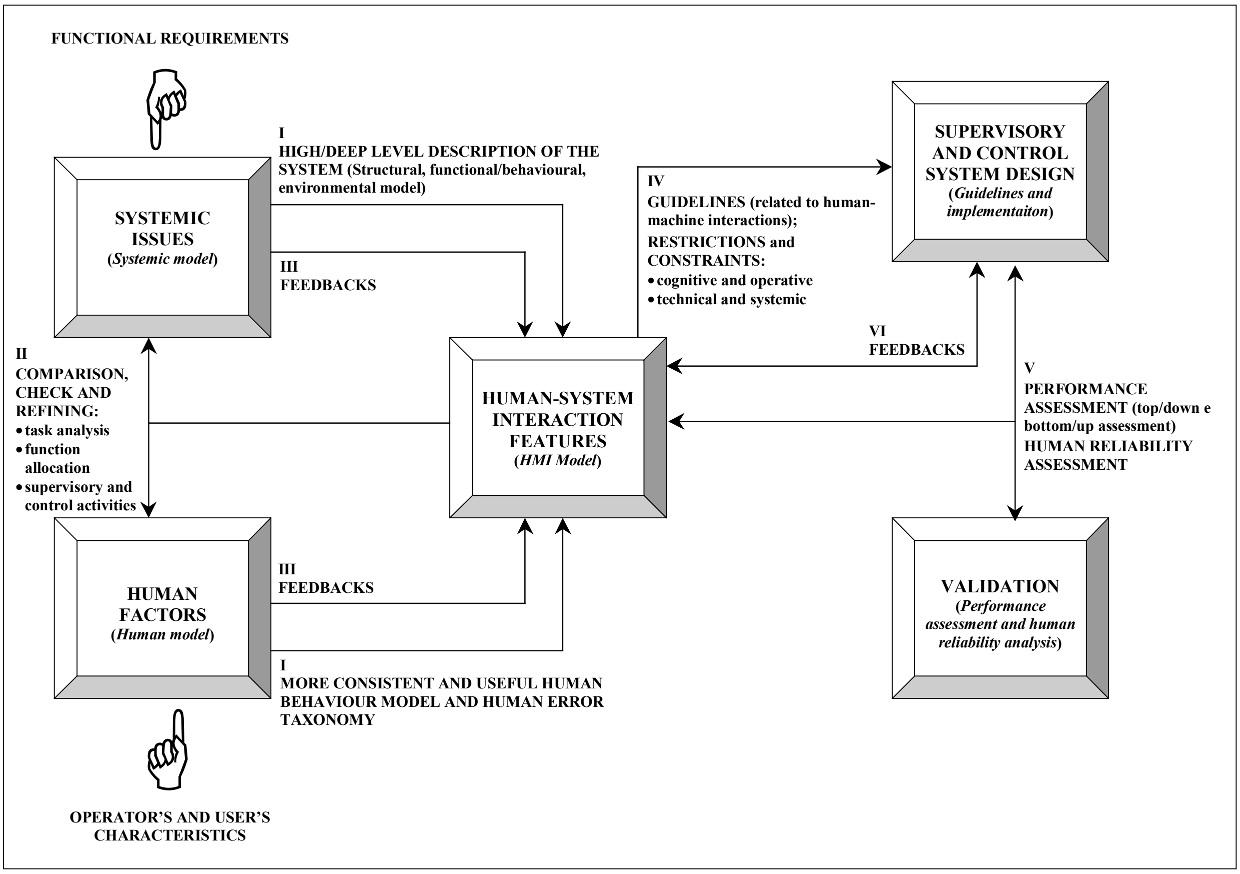


Figure 1 – The proposed methodological framework

- a *Human-Machine Interaction Model*, with selection of the most appropriate representation of relations between operators and supervised/controlled system.

Two final steps are recursive and complementary:
- the *Supervisory and Control System Design phase* implements the information from the previous steps integrating them with "generic" (syntactic, semantic, contextual and environmental issue) and "specific" guidelines (display and control design);
- the *Validation phase*, performed at design stage, relies upon a top-down and bottom-up assessment, and requires a complete human reliability analysis by appropriate techniques.

The details of each phase can be found on the specific publications mentioned in the references [3, 6]. It is important here to highlight the main features of the methodology, that can be summarised as follows.

The first three phases of the framework must be considered strictly interconnected: their goal is to investigate all systemic and human aspects in the definition and design of control system and human-machine interface, as well as to integrate the overall information in a comprehensive model giving a complete picture of the human-machine characteristics. This follows directly from the notion of the previously mentioned JCS paradigm.

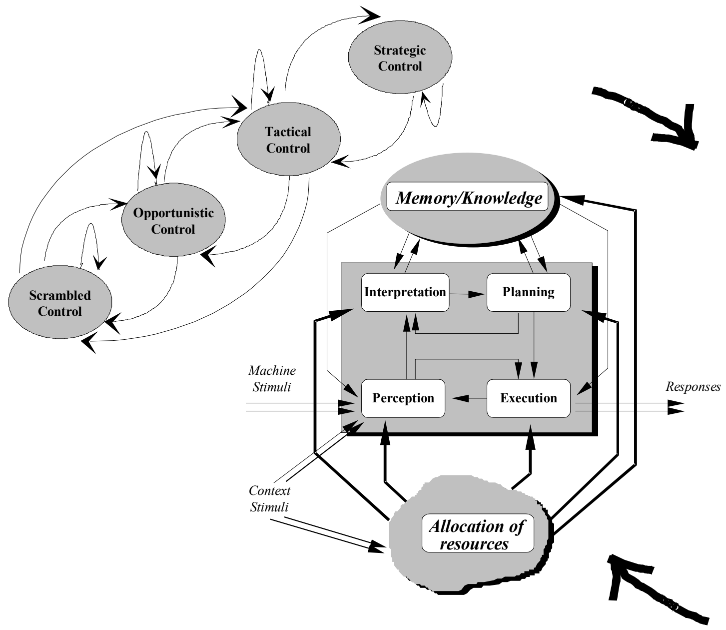
From the human modelling point of view, a particular attention has to be devoted to the identification of operator's characteristics. According to most studies on control room design and human factors related safety, the cognitive aspects of task performance are insufficiently identified and analysed during the design phase, [7]: this can lead to unbalanced human/machine task allocations and poor or inadequate interface design. A fundamental step in a process of control systems and human-machine interface design is then represented by the selection of a reference human model, as it provides a means for the formalisation and organisation of knowledge about the "role" of the human operator. This is an essential information to determine the level of automation and the distribution of tasks between human operator and control system. In addition, it also represents a basic indicator about the kind of operator interface required in a specific situation [8].

The third and fundamental phase of the modelling process is represented by an activity of integration of the inputs from the previous steps and definition of the reference basis of the human-machine interaction for the successive design activities. The so established "triad" has to be faced in a recursive and cyclic way, where the outputs of each phase represent basis and feedback for comparison, checks and refining activities. All these elements contribute to the construction of an overall reference human-machine interaction model, supported by essential activities of allocations of functions (static and dynamic) and task analysis (classical and cognitive).

The actual design phase is a process of translation of all structured and formalised human-system interaction information, and its implementation in a control system and interface design project. This has to be done through development of generic and high level guidelines (syntactic issues, concerning human-computer interaction; semantic issues, regarding human-system interaction; environmental issues) and specific and low level guidelines (actual display and control design).

The validation phase has to be carried out during the implementation of the human-machine system and may demand further design changes . Its contribution becomes crucial not only as a final activity of an accomplished system, but also and above all as a simultaneous assessment of an evolving system. The framework identifies three main phases (top-down assessment, bottom-up assessment and human reliability assessment), that should include evaluation of qualitative and quantitative nature able to take into account for cognitive aspects of human performance, and links and dependencies with the control system and human-machine interfaces, [4, 9, 10].

Each step of the framework is characterised by a number of techniques and methodologies offered by literature and by previous specific works. The selection of the most appropriate of them in relation to the particular case under study, is done merging the *user's needs* (the more cognitive and operative aspects) and the *design restrictions and constrains* (the more technical aspects).



REQUIREMENTS †		COCOM + VSMoC
A. Cognitive model of reference		
A.1	Cognitive functions PIPE	★★★
A.1.1	*Connection within PIPE*	★★★ - Cyc.
A.1.2	*Effects of Context/Machine on PIPE*	★★★
A.2	Allocation of Resources (AoR)	★★★
A.2.1	*Connections of AoR and PIPE*	★★★
A.2.2	*Connections of AoR and Memory/KB*	★★
A.2.3	*Effects of Context/Machine on AoR*	★★
A.3	Memory/Knowledge Base (KB)	★★
A.3.1	*Connections of Memory/KB and PIPE*	★★
B. Design		
B.1	Task analysis	★★★
B.2	Functional modelling	★★
B.3	Individual/team/organisation	★
B.4	Interactions	★★★
B.5	Emergency	★★★
B.6	Taxonomy	★★★
B.7	Operational activities	★★

† The following measures apply:

-	Not treated	★★★	Modelled in detail
★	Implicit consideration	**Seq.**	Sequential
★★	Modelled at minimal level	**Cyc.**	Cyclic

Figure 2 – An example of selection matrix: the case of an operator's behaviour model (COCOM/VSMoC)

This selection and adjustment phases have been structured in selection and evaluation criteria and "aid-to-decision" matrixes, whose test and validation are among the main aims of the real case application. Figure 2 shows an example of a possible selection matrix for the cognitive human behaviour model. In this specific case, the selection is performed in relation to the model capability of representing the relations between the cognitive functions (Perception, Interpretation, Planning, Execution) and the cognitive processes (Memory/Knowledge Base and the Allocation of Resources) of a reference model of cognition, and to support specific kind of activities related to design process. The model under study is, in this example, the COCOM/VSMoC [4]: a similar approach has been performed for each step characterising the different phases of the methodology.

3. The case study application

3.1 The human-machine/system interaction modelling

The selected system, object of the case study application, is the main steam group of a thermoelectric and cogenerative plant in Northern Italy, devoted to electrical power production (142 MW_{el}) and thermal feeding of a district heating network (200 MW_{th}). In particular, the application of the methodological framework has been focused on the control and supervision system of the related alternator/turbine group, with a particular emphasis on the JCS triad approach previously described: a detailed representation of the human-machine interaction has been obtained, allowing firstly to test and validate all the main methodological phases, and secondly to translate these resulting qualitative and quantitative picture in guidelines at different levels (control system and human-machine interface design, contextual and environmental problems, organisational and management issues).

Each step of the methodology has been completely applied, selecting the most suitable among the offered methods and techniques, and fully performing all the modelling phases.

A deep *systemic assessment* has been performed, through collection and analysis of all the available documents, walk-throughs and talk-throughs with expert operators, direct familiarisation with the control room and supervision interfaces: this phase has permitted not only to acquire a deep knowledge about all the main features of the control system (whose structure is partially visualised in figure 3), but also to collect a large amount of information about the working environment, identifying the main "context stimuli" influencing the operators' performances.

In this phase, a particular attention has been dedicated to the *functional analysis* of the systems: a specific technique for thermo-electrical plants [11] has been used, modelling with a very structured and decompositive approach all the features related to functional hierarchies and heterarchies, open and closed control loops, effective function-allocation solutions, main control and supervision variables and parameters. A restricted portion of the wide functional tree is visualised in figure 4 in the next page.

From the human point of view, a particular attention has been devoted to the cognitive aspects of the operational performance: the selection of both the *human model* and of the *human erroneous behaviours classification* has been performed taking into account the capabilities of internal/mental functions and process representation. In this perspective the choice has fallen on the COCOM/VSMoC cognitive model [4] and on the taxonomy associated to the HERMES methodology [11].

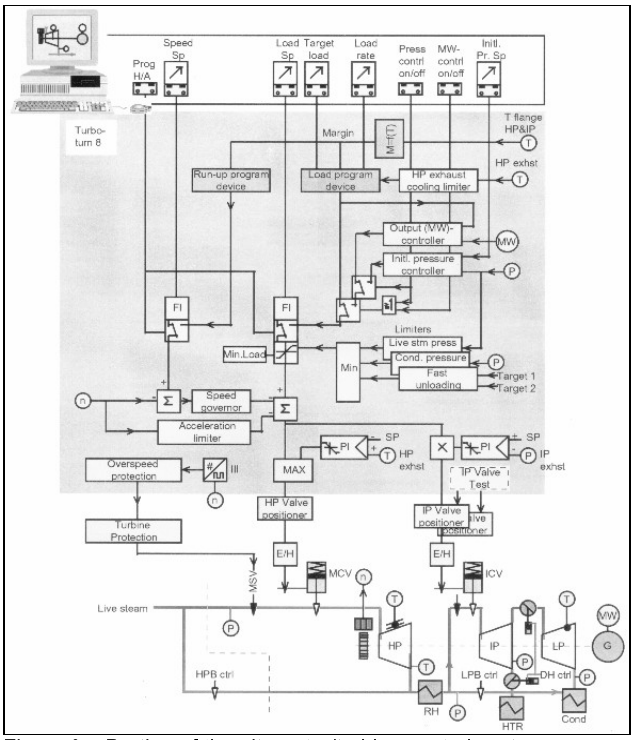


Figure 3 – Portion of the alternator/turbine control system

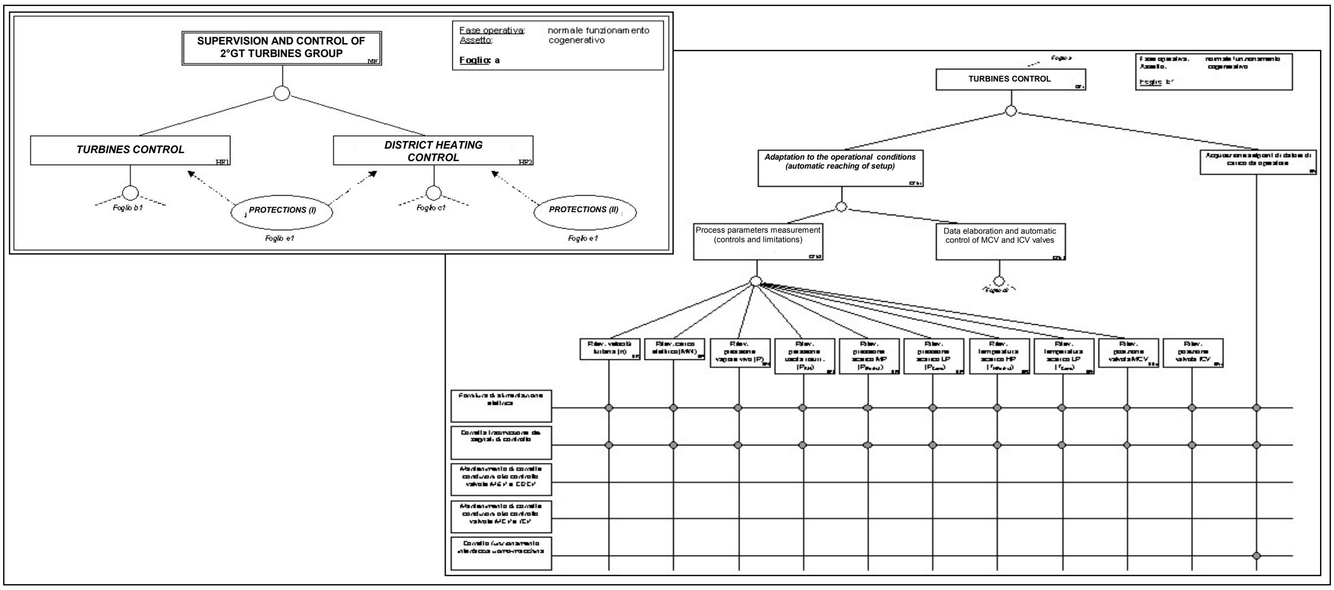


Figure 4 – Portion of the functional modelling approach

On these bases, an accurate *task analysis* has been performed, focusing not only on all the technical and operative aspects, but also on the cognitive features associated with the performance requirements, allowing the reaching of the following modelling results:

- identification and deep description of the main task, and of the generic and specific subtasks related to normal operations and emergency operational sequences;
- building of a specific *cognitive demands profile* associated to the operational sequences, with reference to a list of critical cognitive activities and to a "generic cognitive activity by cognitive demand matrix";
- identification of possible *human erroneous behaviour deviations* and of *cognitive root genotypes* associated to each operative task.

The performing of the systemic/cognitive task analysis has been conducted, from the formal point of view, through a hierarchical and tabular approach (visualised in figure 5). The main cognitive results have been structured in diagrams concerning the different operational phases and the overall normal and emergency sequences, representing the related characteristics in terms of cognitive functions solicitations and erroneous behaviour paths.

All the qualitative and quantitative descriptions so far described, have contributed to the development of an overall and integrated human-machine/system interaction description according to a JCS approach, allowing:

- to formalise all the functional, structural/dynamic and operative aspects of the supervision and control system;
- to highlight the cognitive features of the system operation;
- to put in evidence and to categorise several design-related and human-related problems.

Phase: 3.2	**Description**: Power generation starting (2)								
ID action	**Executor**		**Description**		**Cognitive workload profile**		**Erroneous behaviours**		**Comments**
	Op.	**Sup.**	**General**	**Detail**	**Cognitive activity**	**Cognitive function**	**Classes**	**Specific external causes**	
3.2.4		X	Starting of power generation till the maximum allowed value	oral communication to operator of the order of execution	Coordination	Planning Execution	B1	Proc_Gen; Int_Com; Int_Dis	
3.2.5	X		Actuation of the power starting sequence till the desired value (electric power) and verification of the correct execution	a) setup of an adequate value of the charge controller (by the button "RIF_MW_MODO_AUTO")	Regulation	Observation Execution	B3/B4	Aut_Mez_Obb; Inf_Amb; Proc_Gen; Int_Dis	The regulation of electric power is by open loop
				b) verification of the correct opening of regulation valves (ICV e MCV): correct pursuing of the setpoint (leggibile da "RIF_MW_MODO_AUTO") by the effective charge (readable by "RIF_MW_MODO_MAN")	Regulation	Observation Execution	B3/B4	Aut_Mez_Obb; Inf_Amb; Proc_Gen; Int_Dis	
				c) verification of the increasing of the electrical power, readable from the interface in correspondence of the alternator	Monitoring	Observation Interpretation	A2/A4	Proc_Gen; Int_Dis	
				d) verification of the correctness of values of vibrations, differential expansions and structural temperatures	Scanning	Observation	A1	Proc_Gen; HMI_Pos; HMI_Diff; HMI_Fram; Int_Dis	
				e) verification of absence of active limitations and alarms	Scanning	Observation	A1	Proc_Gen; Int_Dis; Inf_Inc	
				f) verification of the complete closing of bypass valves when 30% of electric power is reached	Monitoring	Observation Interpretation	A2	Proc_Gen; Int_Dis	
				g) adjusting of the value of charge controller (point b) till the reaching of the desired value of electrici power	Coordination	Planning Execution	B3/B4	Aut_Mez_Obb; Inf_Amb; Proc_Gen; Int_Dis	The regulation of electric power is by open loop

Figure 5 – Tabular systemic/cognitive task analysis

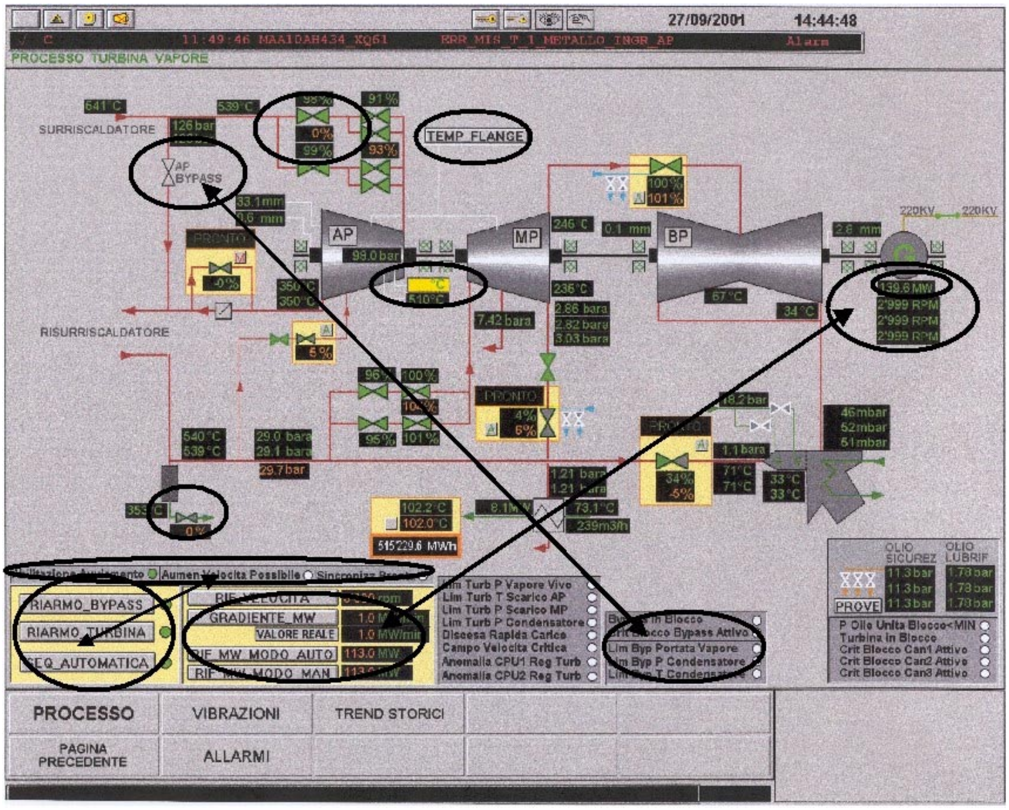


Figure 6 – Highlighted problems on one of the displays of the present human-machine interface

3.2 The development of specific design guidelines

All the amount of qualitative and quantitative indications coming from the modelling phases previously described, was translated in a number of indications and guidelines that can be categorised as follows.

General guidelines: several lacks and problems from the Human Factors point of view, related to management, organisational, contextual/environmental issues, were highlighted: specific solutions have been proposed for each evidenced matter.

Specific design guidelines related to the present human-machine interface: all displays of the present HMI have been object of a deep inquiry, especially during the phase of systemic/cognitive task analysis. As it is shown in figure 6, the modelling phase allowed to relieve several problems of syntactic and semantic nature in the supervision and control features of the system, from the point of view of bad functional grouping, incoherence of graphical and qualitative data presentation and devices representation, fractioning of controls on different systems to be grouped in one single interface, and so on. A process of re-design of the main displays has been performed: figure 7 shows the proposed solution for the display analysed in figure 6.

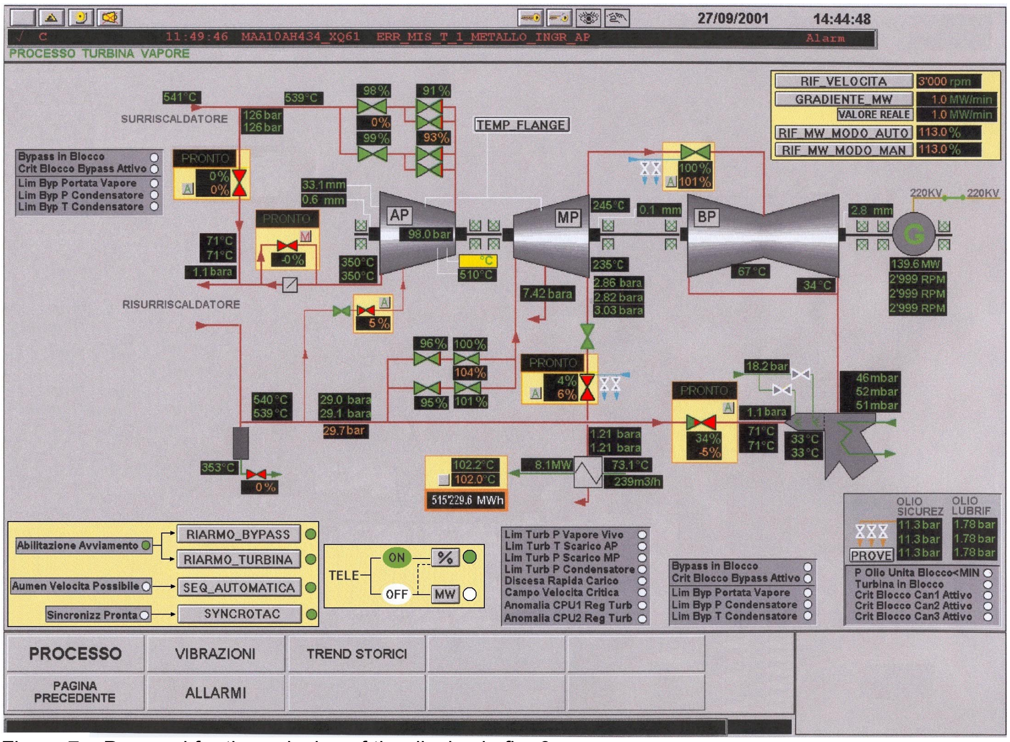


Figure 7 – Proposal for the redesign of the display in fig. 6

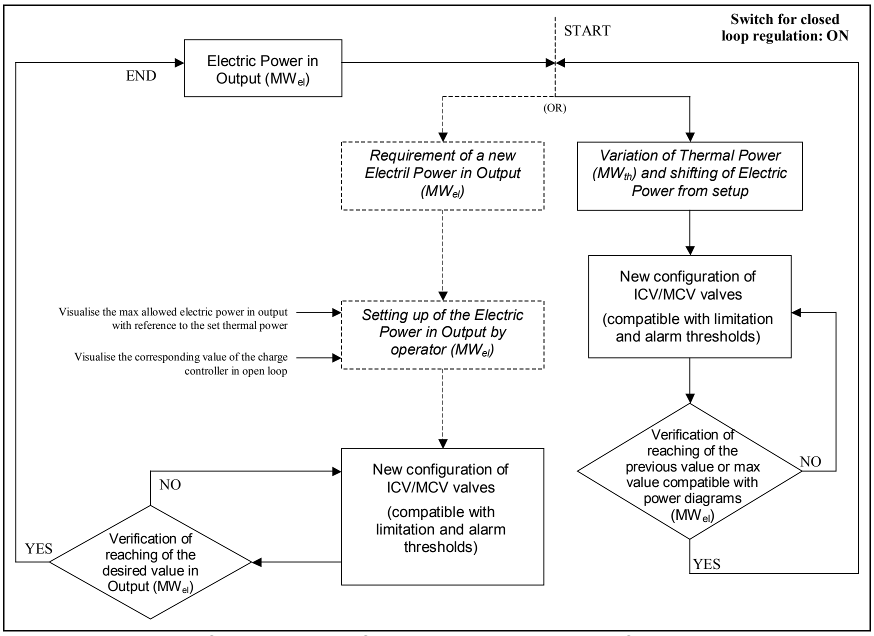


Figure 8 – Example of proposed modifications to automation and function allocation

<u>Specific design guidelines related to level of automation and function allocation</u>: a number of automation-related problems have been identified during the modelling phases, especially from the interactions between the functional modelling and the systemic/cognitive task analysis. In figure 8 an example of possible automation/function allocation guideline proposal is shown. It represents a potential design solution aiming at switching the present approach for electric power setting based on an open loop, in which the operator has to set the control valves configuration of the system and not the electrical output: this requires several iterative controls/commands by the operator and an inadequate cognitive and error-promoting workload. A new configuration based on a closed loop is proposed, in which the operator can set the effective value of electric power in output and can follow the establishing of the automatic configurations made by the control system.

<u>Specific design guidelines for new supervision interface panels</u>: several problems have been highlighted by the human/machine interaction model, especially concerning the support capabilities to monitoring and diagnosis activities (in normal conditions and, above all, during emergency situations). The cognitive task analysis has in fact revealed that the present structure of the supervision system (topological view, high detail in visualisation of data and parameters, low level of abstraction) is more adapt to support the control and regulation activities. Some possible solutions in order to resolve this lack, very serious for the cognitive workload profile, have been proposed. In figure 9, as an example, an advanced monitoring and diagnosis panel is shown: it is based on the Mass Data Display (MDD) approach, on a functional grouping structure and on a fuzzy representation of the state of the main parameters identified during the HMI modelling phases (by 9 different shades from red to green). This approach, theorised in other works developed by human factors researchers [12], allows the operators to acquire a continuous and immediate overview and awareness of the global state of the system, identifying possible incipient anomalous conditions of fundamental parameters even if distant from alarms states or conditions of intervention of the protection system.

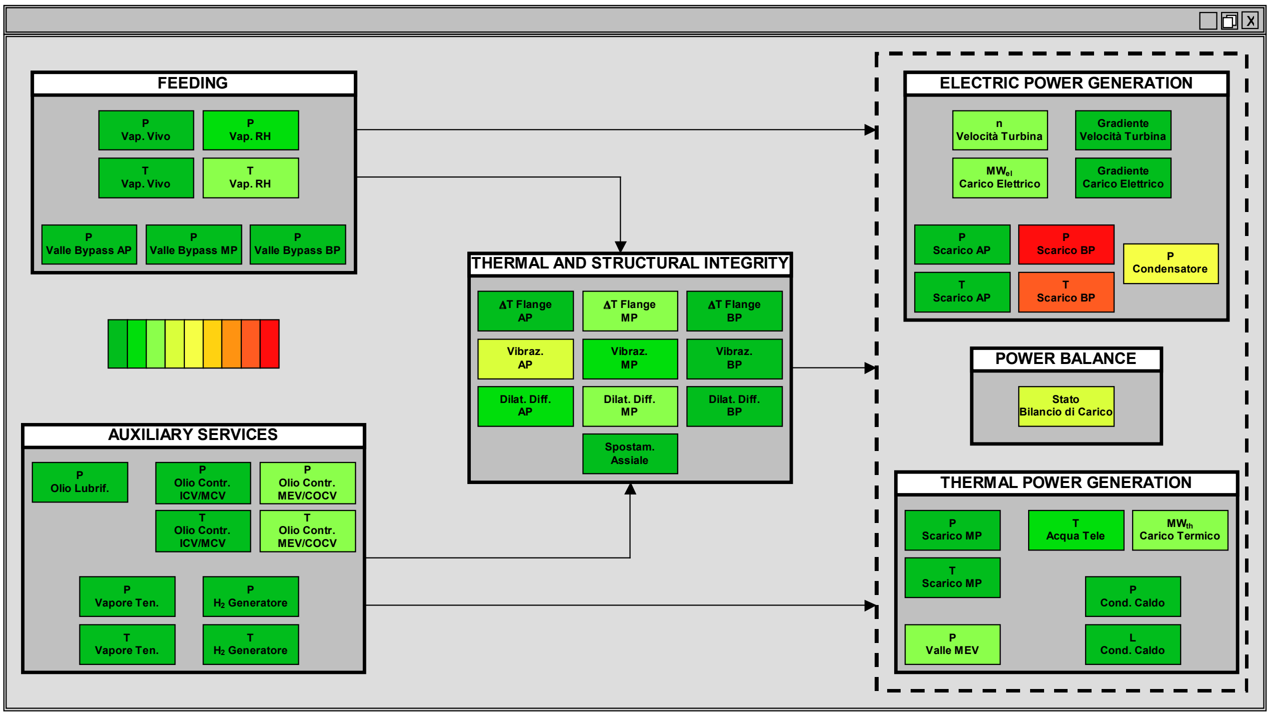


Figure 9 – Example of new supervision interfaces: an advanced monitoring and diagnosis MDD panel

4. Conclusions

The main purpose of the PhD activity (1998-2001) presented in this paper has been the development of a support methodological framework for designers of human-machine interactions. By means of a number of articulated and well formalised phases, the methodology aims at supplying the designer with a structured guide through all "theoretical" aspects and more "practical" issues arising during a design activity. The framework offers a guideline and a compendium of existing techniques for designing and developing HMIs, that merge in the exploitation of the concepts of the *Joint Cognitive System* paradigm.

In the second phase of the research activity the application to a real case has been performed. The object of the study was the control of the turbine/alternator system of a thermoelectric power plant in Northern Italy. The outcome of this exercise has been dual. On the one hand the methodological framework and its recursive procedure has been validated with respect to the concepts of JCS-triad and to its practicality to a real case. On the other hand, it led to appreciate the amount of modifications and amendments that are required in the reality to comply with the requirements of a cognitive approach, with respect to a planned process of renewal of a control system based on more classical engineering methods.

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