Intelligent Interfaces Based on Fuzzy Logic: Example with a Human-Error-Tolerant Interface Approach

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Summary. The intelligent human-machine interaction domain is huge and rich in concepts, methods, models and tools. Fuzzy logic can be exploited for designing current approaches contributing to intelligent interfaces. As an illustration, this chapter describes the development of a intelligent human-machine interface which is tolerant of human error during the control of a simple industrial process. Human-error-tolerant interfaces (HETI) should be applied to industrial processes in order to keep the human operators sufficiently vigilant to enable them to handle unexpected events. With this goal, a global architecture is proposed; it integrates a human operator model (concerned with possible human actions and potential errors). For the design of this model, preliminary human behaviours and errors during the control of a simulated process have been analysed. This enables to devise general rules, to be used when programming such an interface, using fuzzy logic. The Human-error-tolerant interface design and evaluation are described.

Key words: Human-machine interface; intelligent interface; human error tolerance; fuzzy logic; human behaviour; human operator model.

1 Introduction

Today's increasingly complex industrial systems require highly skilled operators, who need to control several parameters at once in control rooms (Rasmussen, 1986; Gilmore et al., 1989; Kolski, 1997; Moray, 1997). These human operators have often to perform complex cognitive tasks, in various situations, that the automatic devices are not able to realize (Sheridan, 1988; Hoc, 1996). This implies that human reliability should be ensured (Swain and Guttman, 1983; Hollnagel, 1994; Laprie et al., 1995). Certain circumstances may bring about grave errors, even with reliable operators (Rasmussen and Vicente, 1989; Reason, 1990; Senders and Moray, 1991).

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One way of avoiding such errors is to develop specialised, intelligent (or adaptive) help systems. In fact, the research domain concerning intelligent interfaces is important at the international level and very rich in concepts, methods, models and tools (Hancock and Chignell, 1989; Schneider-Hufschmidt et al., 1993; Kolski et al., 1992; Avouris et al., 1993; Roth et al., 1997; Kolski and Le Strugeon, 1998, Höök, 2000).

The Human-Error-Tolerant Interface (HETI) corresponds to a special kind of intelligent interface; this concept was proposed during the 1980s (Rouse and Morris, 1985; Coonan, 1986); one that is aimed at minimizing the consequences of certain human errors by keeping human operators alert in the face of an unexpected event. In order to be truly efficient, the HETI has to understand the human actions, and correct them in cases of error. It is why the preliminary analysis and modelling of the human errors is a very important step in the design of the so-called "human error tolerant interfaces". The model must be coherent with what the human operator has to do in summing the application.

Based on (Beka Be Nguema et al., 2000), this chapter is composed of three main parts. In the first part, intelligent interface approaches are classified and examples of approaches using fuzzy logic are given. In the second one, the global principles of the HETI are defined. This part explains akso preliminary experiments aimed at studying and modelling human errors that would be tolerated by the HETI to the greatest degree possible. Based on the data obtained from the preliminary experiments, a HETI is described. Of course, this HETI must be considered as a laboratory prototype, aimed at proving the feasability of such an approach. This HETI was designed using fuzzy logic, which is the practical artificial intelligence method for operator-activity modelling (Rouse and Rouse, 1983; Cacciabue et al., 1990; Shaw, 1993). The main appeal of fuzzy-logic models is that they take into account the imprecisions and uncertainty of human judgement (Zadeh, 1965; Kaufmann, 1972; Pedrycz, 1989; Yager and Filev, 1994; Cox, 1998). The evaluation of the HETI, tested within a laboratory (controlled) environment, is explained in the last part of this chapter.

2 Intelligent Interface Approaches

A major role of HMIs is to bridge the gaps which exist between humans and machines (Card, 1989). In this perspective, research on so-called “intelligent” interfaces appeared at the beginning of the 1980s. A common definition of an intelligent interface is one which provides tools to help minimize the cognitive distance between the mental model which the user has of the task, and the way in which the task is presented to the user by the computer when the task is performed (Hancock and Chignell (1989)). According to Chignell et al. (1989), an "intelligent" HMI is an "intelligent" entity which mediates between two or more interactive agents, each of which has either imperfect understanding of the way in which the others act, or an imperfect understanding of the way in which the others communicate. A global classification about intelligent HMI will be presented. Then examples of intelligent HMI based on fuzzy logic will be given.

2.1 Global Classification

In what follows, we define an "intelligent interface" as any human-machine interface that contains components, which make use of the properties of Artificial Intelligence. Thus we would apply the term to any interface which makes use of, or includes, a knowledge base, a planning mechanism, or heuristics. Equally, we include in our definition interfaces which make use of concepts relevant to Distributed Artificial Intelligence, including functions embodied as agents, including intelligent agents, autonomous agents, intentional agents, etc. (Ferber, 1995; Logan, 1998). As explained in (Kolski and Le Strugeon, 1998), most interfaces have an important characteristic in common, namely adaptability. They differ, however, in how adaptability is achieved: Figure 1 classifies five main types of systems by their degree of intelligence:

- flexible (or adaptable) interface (which we do not here consider to be inherently intelligent) allows adaptation to the preferences of the user, and according to the system in which it is used (Waern, 1989). Note also the very interesting proposition concerning « co-evolution » of interacting systems in which the user contribute directly to the evolution of the tools at his/her disposal by taking into account the acquired experience (Bourguin et al., 2001).
- The human-error-tolerant interface takes account of the behaviour of the user (Rouse and Morris, 1985). This chapter will be focussed on this type of intelligent interface: an approach based on fuzzy logic will be described.
- An adaptive HMI, in itself, should take into account the two previous approaches, but generalise them, and adapt itself to the cognitive behaviour and the tasks of the user (Edmonds, 1981; Kolski et al., 1992, 1993; Schneider-Hufschmidt et al., 1993). New concepts have appeared in the literature, such as context-aware applications (Dey et al., 2001) or HMI plasticity (Thévenin and Coutaz, 1999).

- An Operator Assistant, while having in principle the same abilities as an intelligent interface, has further levels of autonomy, and behaves almost like another human assistant (or co-pilot) (Boy, 1991; 1997). Guy Boy, one of the leaders in this area as a result of his work for NASA on "Intelligent Operator Assistant" projects, gives the following example: *"In an aircraft cockpit, a human co-pilot shares the work with the captain, but does not have the final responsibility: the captain is the captain! The captain can consult his co-pilot at any time during the flight, but the former has the ultimate responsibility. If the captain delegates part of his responsibilities to the co-pilot, then that responsibility becomes a task for the co-pilot to perform. Furthermore, the captain can interrupt a co-pilot's task at any time if he thinks it necessary. However, a co-pilot can take personal initiatives, for example to test parameters, keep himself up to date with the development of a situation, predict which tasks can be foreseen, etc. A co-pilot can make use of the instructions in an operating procedures manual to the request of the pilot. He must be able to explain, at an appropriate level of detail, the results of any such use."* Note that an operator assistant can also be modelled as an agent (see below).
- An intelligent agent has in principle all the above characteristics, but in our opinion represents the arrival of a truly "Intelligent" interface because of its ability to model cooperative human-machine systems, or even socio-technical systems (Wooldridge and Jennings, 1995; Grislin-Le Strugeon et al., 2001; Mandiau et al., 2002): the notion of an intelligent interface using the concepts of intelligent agent(s) arises from the possibility of decomposing the human-machine system into a set of agents. These agents would work in parallel or would cooperate, with the goal of solving their relevant problems in the light of the task to be performed. The results of their activities would be transmitted to the users, but at the same time they would perform a large number of other operations, for example to control the system itself. This domain is the subject of numerous current researches; see for instance (Keeble and Macredie, 2000; Klusch, 2001; Ezzedine et al., 2005).

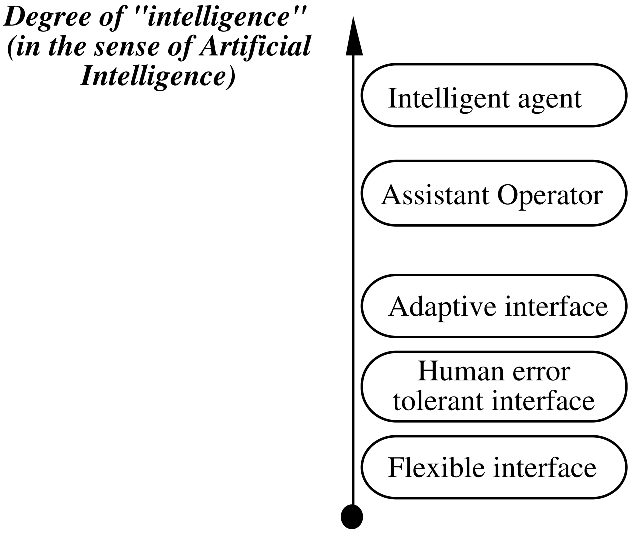

Fig. 1. Types of intelligent interfaces (Kolski and Le Strugeon, 1998)

2.2 Examples of Intelligent Interfaces Using Fuzzy Logic

Modelling technics and tools used in the current intelligent interface approaches are various: rule-based approaches, neural networks, bayesian networks, and so on. More and more approaches are based on fuzzy logic. Five representative examples (one for each type of intelligent interface) are given below.

Flexible interface

Ribeiro and Moreira (2003) describe a flexible query interface built for a relational detabase of the 500 biggest non-financial Portuguese companies. The interface is based on fuzzy logic in which queries in natural languages with pre-defined syntactical structures are performed (for instance, “Has company X a high financial health?”), and the system uses a fuzzy natural language process to provide answers (for instance, “Financial health is average (43 %), because cash flow is above_average (61%) […] solvency is very small (14%) financial autonomy is high […]”).

Human-error tolerant interface

Pornpanomchai et al. (2001) are interested in situations in which the user do not use a keyboard to interact with a computer. They propose a non-keyboard computer interaction by using a write-pen or mouse to write Thai handwritten characters and words. In their approach, the fuzzy logic set is used to identify uncertain handwritten character shapes (in such approach, we can consider as an error a badly written character or word). There tests show precision results equal to 97.82%.

Adaptive interface

Mäntyjärvi and Seppänen (2003) are focused on the adaptation of applications representing information in handled devices: in these applications, the user is continuously moving in several simultneous fuzzy contexts (for instance the environment loudness and illumination). These authors explain that context-aware applications must be able to operate sensibly even if the context recognition is not 100% reliable and there are multiple contexts present at the same time. Mäntyjärvi and Seppänen propose an approach for adapting applications according to fuzzy context representation. User reactions indicate that (1) they accept adaptation while insisting on retaining the most control over their device, (2) abrupt adaptations and instability should be avoided in the application control.

Operator assistant

During the MESSAGE Project of analysis and evaluation of air-craft cockpits (Boy, 1983; Boy and Tessier, 1985), an operator assistant (copilot assistant) has been designed and evaluated. It is able to generate and execute tasks either in parallel (automatisms), or in sequence (controlled acts). With the aim to reason like a (simplified) copilot, such an assistant is characterized by a cognitive architecture; in its long term memory, so-called situational and analytical representations are implemented and accessible. Fuzzy logic has been used to model different types of situations. For instance, at a given time the *perceived* situation is a particular image of the local environment and is characterized by incomplete, uncertain and imprecise components; the *desired* situation is composed with a set of (fuzzy) goals which the operator intends to reach.

Interface using intelligent agents

Agah and Tanie (2000) propose intelligent graphical user interface design utilizing so-called fuzzy agents. The objective of these agents is to understand the intents of the user, and to transform the deduced intentions into system actions. For instance the motions of the mouse cursor can be interpreted by the agents and the mouse cursor can be moved according to the conveyed intentions; in these conditions, the amount of work required by the user can be reduced. The agents are specialized for different system states and/or situations (environment characteristics, task features…). Each agent is implemented using fuzzy logic control and uses a set of fuzzy rules making possible the identification of user intentions and the proposition of system actions.

3 Illustration: A Human-Error-Tolerant Interface (HETI) Based on Fuzzy Logic (Beka et al., 2000)

3.1 HETI: Global Principles

The development of interfaces that are tolerant of human errors is, in practice, based on preliminary studies of the kinds of errors that humans make in simulated and/or real conditions. In these studies, errors are identified by recording actions that result in the behaviour of the human-machine system failing to meet well-defined criteria of productivity or safety. The idea is to use such studies to develop ways which, in the real world, will make it possible to replace, improve or negate inappropriate human actions (Rouse and Morris, 1985; Hollnagel, 1989, 1994; Beka Be Nguema et al., 1993; Masson and De Keyser, 1992; Masson, 1994). There is no unique or unified architecture for a HETI to be found in the research literature.

A possible architecture of such an interface could consist of three major modules (Figure 2). A decoding module translates the human actions (i.e., the input commands of the human operator) into data that the HETI can use. A second module first identifies the human actions in all control situations. It is based on: (1) a *human actions model*, which describes what the human operator can do in all possible control situations, and (2) a model of the industrial application, which describes what should be done by the human operator in all possible control situations. This second module can then correct the actions in the event of human error. In the research literature, the *human actions model* and the *application model* can be combined into a so-called *human operator model*. This chapter uses this terminology (*human operator model*). A third module is concerned with presentation of information on a graphical screen. It has two roles: it presents the state of the process variables, according to different presentation modes, and it explains to the human operator the problems that the HETI has diagnosed and the advantages to be gained from its proposed intervention (feedback from the module #2).

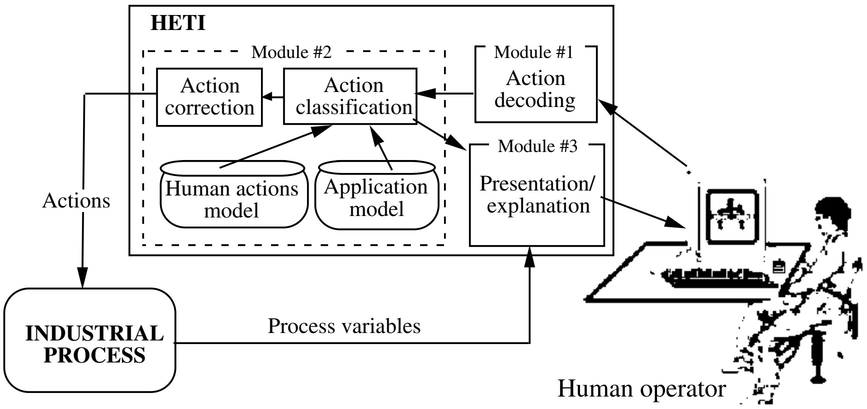

Fig. 2. Global architecture of a HETI (Beka Be Nguema et al., 2000)

3.2 Preliminary Experiments Aimed at Studying and Modelling Human Errors

One of the aims of the HETI is to identify the human operator's action. In the event of human error in context of the application, that action must be corrected. Whatever the application, it is necessary to be aware of what errors the human operator is likely to commit. This is made possible by carrying out preliminary experiments, in a real context or by simulation, with operators, and by observing the errors that they commit during the performance of their process-control tasks. Without knowledge of the possible errors, it is impossible to design the HETI. The goal of the preliminary experiments was to define the specification for the human operator model, to be integrated into the HETI. To achieve this, a study of human operator behaviour during the course of a simple simulated process was conducted, under various task configurations. Analysis of the experimental data allowed classification of the various kinds of behaviour, as well as the kinds of errors encountered in each task configuration. The task configurations used in the study are: presence of thermal inertia, presence of graphic deterioration, and double tasking (with two different tasks):

- A manual task of temperature adjustment, in which the simulated industrial process is a quadruple heat exchanger. This process consists of a cooling system that takes hot water at a temperature (T_{1e}), and flow rate (Q_{1e}), and then cools it using cold water at a temperature (T_{2e}) and flow rate (Q_{2e}). The system is made up of four heat exchangers: e_1, e_2, e_3 and e_4. These are connected in series on the hot-water circuit, and are fed cold water in parallel (see Fig. 3). Each exchanger is controlled by an up-flow dispenser, respectively named d_1, d_2, d_3 and d_4, which sends cold water into the exchanger and redirects it into a secondary pipe when switched off. A similar dispenser, called d_0, controls the hot water input in the cooling system. This redirects hot water into a secondary pipe when switched off, as would be the case in an emergency shutdown.

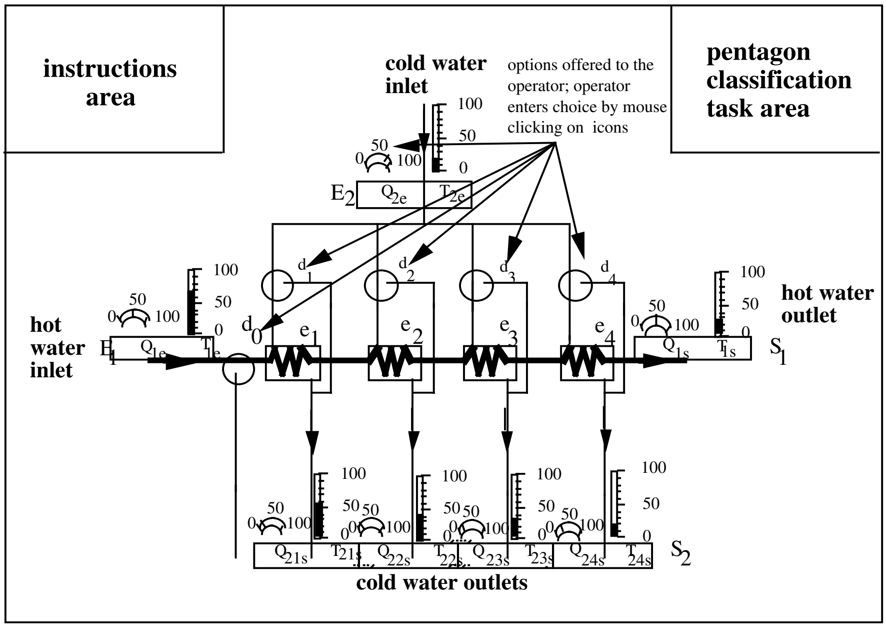

Fig. 3. Diagram illustrating the industrial process.

Figure 3 appears on a graphic screen in front of the subject. The upper left-hand part is where instructions are given to the subject. Temperatures are represented by bar graphs; flow rates are represented by dials. The upper left-hand area is used for a pentagon classification task.

- A second task consists of classifying a series of pentagons. In this classification task, 36 randomly selected pentagons, of any size, are displayed, one by one on the screen. From these, eleven pentagons belong to the "very large" category, eight to the "large" one, five to the "medium" category, four belong to the "very small" one. Each display comes with a multiple-choice question and a space where the operator enters a self-evaluation of the certainty on a scale of 0 to 1, where 0 indicates null certainty and 1 indicates complete certainty about this classification (this gives an evaluation of the degree of confidence of the human operator in performing the task). This pentagon-classification task is an often-used and well-documented study in the authors' laboratory (See for instance Desombre et al., 1995; Louas et al., 1998). It was selected for the present study to increase the complexity of the human task. Moreover, it uses very different assessment skills from those used in the first task. The human operator influences the process manually by clicking icons, and enters answers for the pentagon-classification task in the same way.

- These two tasks can be combined (under a so-called "double task" in the experimental tradition), including both the temperature adjustment task and the classification task.

In order to prove the feasibility of the HETI design, two relatively simple tasks have been chosen. These tasks are not an accurate reflection of the many complex situations found in industry, and particularly in the control rooms of dynamic processes; thus, the results cannot be directly extrapolated to such complex processes. These tasks have been chosen because they allow the human behaviours and errors to be exhaustively identified during the preliminary experiments (this is very important in such exploratory researches); these tasks are also sufficient to overload the human operators, and thereby test their ultimate capabilities as regards error generation. For more complex processes in which the situations can prove to be too numerous to be studied in an exhaustive manner, it is a matter of studying whether it is possible to decompose the process into several simpler sub-systems. In that case, it then becomes possible to apply the same approach to one or several of these sub-systems. This is a research line in its own right which, to the authors' knowledge, has not been studied at international level.

3.2.1 First Experiment (Single Task)

In the first experiment, conducted with 44 subjects (also called "human operators" in chapter section, even though the subjects are not real operators, but university students), the main human task consists of keeping the outlet temperature constant. First, each human operator (i.e., each subject) is instructed to aim for a temperature of between 20°C and 30°C in the outgoing hot water (T_{1s}). To achieve this, the operator may adjust the cold-water flow from Q_{2e} in increments of 10 m^3/s. The operator also has control over the on/off switches of the main hot water dispenser (d_0) and the individual heat exchangers. The operator is provided with continuous temperature and flow-rate readings from the hot water and cold water circuits, as shown in Fig. 4(a).

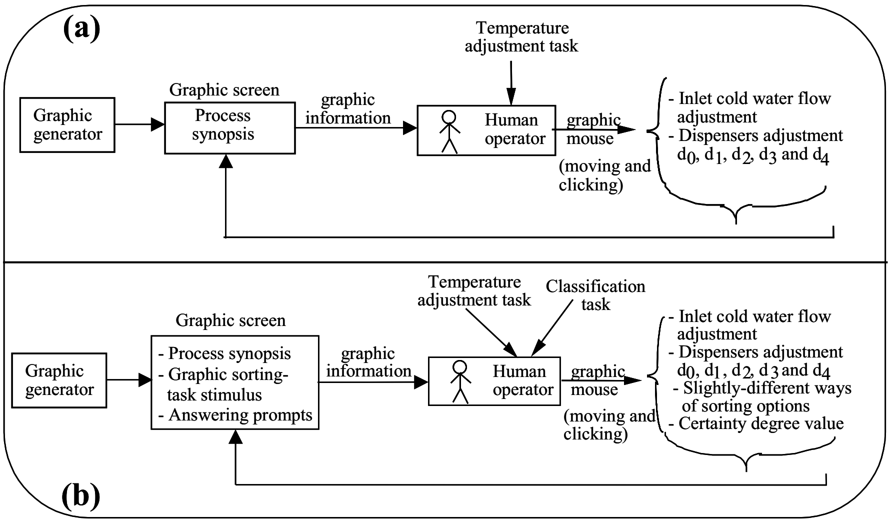

Fig. 4. Experimental system (a) Single task; (b) double task

The test consists of twenty iterations, each lasting twenty seconds. The number of temperature adjustment sequences has been fixed at twenty to provide more easily exploitable scaled results assessment. Operator-performance evaluation is accomplished by counting the number of acceptable temperature adjustments achieved by the operator over the course of the 20 sequences that the operator undergoes. An acceptable temperature adjustment is one where the desired final temperature (20°C-30°C) is achieved in less than 20 seconds. Any sequence where the desired temperature range cannot be reached within 20 seconds, or where the d_0 dispenser is used to stop the temperature-adjustment sequence, is deemed unacceptable. The human operator is unaware of the 20 s time limit. This limit was decided upon following test trials, done to validate the protocol, where 20 seconds was sufficient time for any operator to perform the task under normal operating conditions (to be defined later). However, the operator was asked, at the beginning of the test, to achieve the very best possible results.

This first experiment is divided into four stages: (1) a training stage, which enables the human operator to get familiar with the process; (2) a stage during which the temperature of the cold water inlet (T_{2e}) does not change; during this time the temperature and flow-rate of the hot water inlet vary between 10 and 100; these changes occur every 20 seconds (this stage corresponds to normal operating conditions); (3) a stage where the above conditions deteriorate due to the addition of error-inducing, graphic-data alterations; the aim here was to bring the human operator to produce an error behaviour. During the stages (2) and (3), the cold-water inlet temperature is 15°C. Hot-water inlet parameters are shown in Fig. 6. During the second stage, graphic data alterations P_1, P_2, P_3 and P_4 are introduced. Finally, (4) there is a stage similar to stage (2), with the addition of thermal inertia in the outgoing hot water (T_{2e}). This inertia was selected so that temperature would seem to change slowly. The temperature variation delay may be adjusted according to the intended goal. The optimal value, obtained after preliminary testing, is 0.25 s/°C.

3.2.2 Second Experiment (Double Task)

For this second experiment, 28 of the 44 subjects were available. In the second experiment, each operator is to undertake the following tasks, illustrated in Fig. 4(b): one temperature-adjustment task, as described above, one pentagon-classification task which involves classifying 36 pentagons (appearing one by one on the graphic screen) according to pre-existing templates, then self-evaluating the certainty of this classification on a scale of 0 to 1. This second experiment is divided into three stages: (1) a training stage for the pentagon-classification task, (2) the pentagon-classification task, (3) double tasking, induced by the addition of the pentagon-classification task to the temperature-adjustment task. In every classification task, 36 pentagons are displayed, one by one, on the screen. This number was selected so that the two different tasks would take the same time. The test sequences are shown in Figure 5.

Pentagon appearances are synchronised with the beginning of the sequences; one new pentagon for every two sequences at first, then one pentagon per sequence, then two, then four (the pentagon display rate regularly increases so as to further complicate the task)

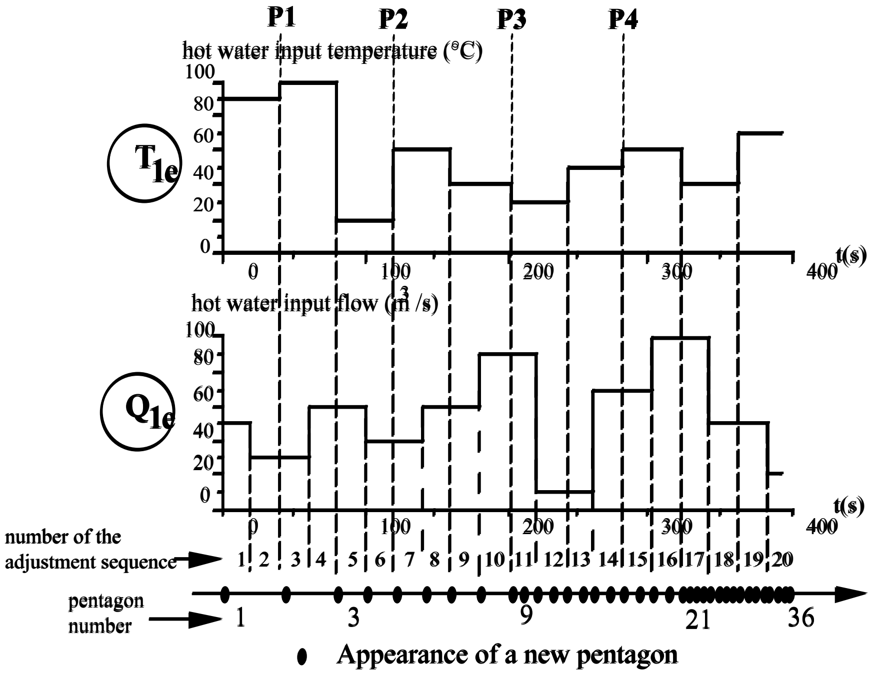

Fig. 5. Test sequences, showing changes in temperature and flow rate on the incoming hot water line. P1, P2, P3 and P4 mark the points at which the graphical display undergoes progressive deterioration (during the second of the two test phases only). P1: all thermometer outlines disappear, and outgoing hot water thermometer starts to behave erratically, P2: outgoing hot water thermometer disappears altogether, P3: outgoing cold water thermometers start to behave erratically, P4: outgoing cold water thermometers disappear altogether.

3.2.3 Results

Each experiment starts after the subject has completed an anthropometric identification questionnaire. This lasts from 40 to 60 minutes, according to the time needed by each operator to become familiar with the process. During the temperature-adjustment stage, the data collected are the variations in temperature, flow-rate and dispenser status parameters over time. At the end of the experiment, subjects are required to fill out another questionnaire; this time concerning the operator's perceptions about the experiment, data deterioration, and whether any available means were left either unused or little used by the operator during the experiment.

The results were processed using classical descriptive statistical methods (Snedecor and Cochran, 1989; Hardy and Bryman, 2004). Cumulative curves, histograms and hierarchical classification were used in the process. These results are fully described in (Beka Be Nguema, 1994). Forty subjects underwent the temperature-adjustment task experiment without data deterioration but with thermal inertia added; of these, 28 also underwent the double-task experiment. Some facts could be noted following the experiments: subject reaction times and the duration of the adjustment were both longer in the case of an unacceptable adjustment than in the case of an acceptable adjustment; subjects either used every adjustment parameter available, or used only the cold-water flow-rate, in the temperature-adjustment task; some errors were due to the operator's inability to estimate the limits of the acceptable temperature range, thus causing slight 'oversteering'; an analysis of the subjects' answers in the after-experiment questionnaire showed that the subjects took into account only the outlet parameter and the adjustment variables when conducting the task.

Subjects were classified according to their performance, which was defined as the number of acceptable adjustments achieved over the total adjustment sequences. Only one subject had a performance of less than 10/20 when doing every temperature-adjustment sequence. Most subjects had a performance over 12/20. Two subjects' strategies gave good results. The first one, used by all but one of the subjects, was to use every available parameter: only the cold-water inlet at first, then the dispensers as needed. Another strategy, used by the remaining subject (who was the exception), was to use only the cold-water inlet, even if two sequences were then impossible to achieve.

Three kinds of behaviours were encountered among the subjects: (1) the "high-risk" takers: these continued the task even when insufficient information was available, or when they did not use "upstream" information; (2) the "measured-risk" takers: these continued the task until a certain critical point (varying from one subject to another) was reached, and then preferred to stop the process; (3) the "no-risk" takers: these stopped the process by activating the emergency d_0 dispenser as soon as something was amiss, especially during the data-deterioration stage.

Four main kinds of errors were observed. These are, from the most frequent to the least frequent, as follows: (1) errors caused by *lack of attention* (Reason, 1990); when the operator used the emergency shutdown during the temperature-adjustment task without thermal inertia and without data deterioration; (2) intended "errors" due to the operator's *lack of motivation* which can be seen during non-critical sequences of the first stage (the subjects concerned do not admit to these errors, which are therefore difficult to analyse); errors caused by *lack of understanding* (Reason, 1990), which are typical of the beginning of the temperature-adjustment task without thermal inertia and without data deterioration; behaviour is hesitant; these could also be delayed lack-of-attention errors; errors due to *poor estimation of the results* (Leplat, 1985); these occur when the operators poorly estimate the outlet hot water temperature or the size of the pentagon. These errors have been considered in the HETI design.

3.3 HETI Design Based on the Data Obtained from the Preliminary Experiments

3.3.1 From Strictly Manual to Automatic Functioning Modes

The system can work using any of the five modes seen in Fig. 6. In the "strictly automatic" mode, an automatic process-control system is implemented by the HETI when requested by the human operator. Actually, the process-control system is a fuzzy controller. The human operator has no further direct control over the process when using this mode. The strictly automatic mode could be useful to an inexperienced operator, by indicating the appropriate method of handling the process. The "strictly manual" mode can only be activated on a request from the human operator. It gives the human operator total control over the process. When this mode is activated, the HETI is prevented from interfering with the process. The "temporarily manual" or "normal" mode is the default functioning mode of the system. In this mode the system is controlled by the human operator, but the HETI is active. The "temporarily automatic" mode can only be activated by the HETI, following a human error. The HETI leaves this mode as soon as the process reaches a non-critical state. It uses the same fuzzy controller as the "strictly automatic" mode. The "transitory" modes are temporarily activated during the transition from the automatic to the manual mode, or vice versa.

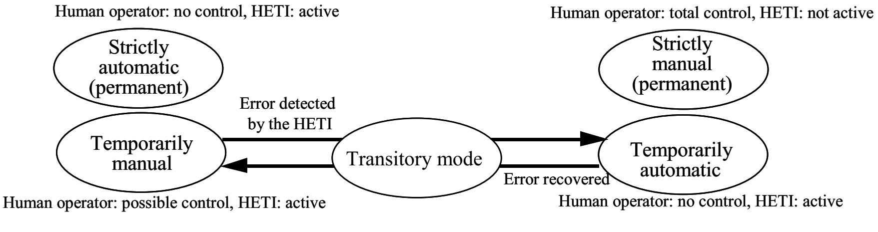

Fig. 6. HETI functioning modes

In addition to the above modes, a help (advisory) function was defined. The purposes of this function are (1) to warn the human operator that an error has probably been made and (2) to give advice on the correct course of action. These actions are the same as those that would be taken by the human-operator model if the HETI were active.

The "strict" modes are permanent modes, where the HETI has a passive role towards the operator, and cannot initiate any change of modes. The "normal" and "temporarily" modes allow the HETI to take an active role in the process.

A three-button menu, related to the functioning modes, was defined. This is accessible via the graphic screen by the human operator. The three buttons are called respectively: AUTO, MANU and HELP (Fig. 7). The AUTO and MANU buttons are mutually exclusive, i.e. selection of the AUTO button deactivates the MANU button, and vice versa. The HELP button works independently of the other buttons.

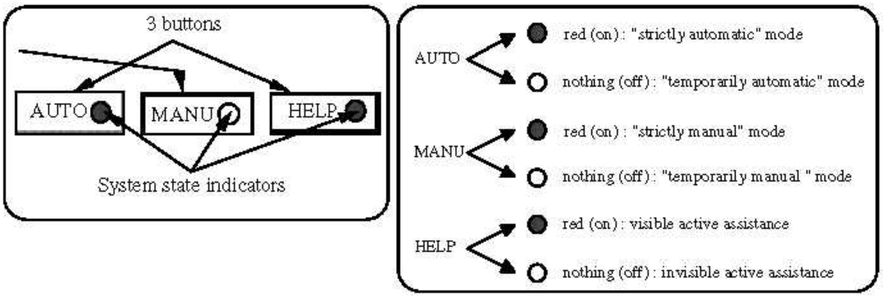

Fig. 7. Mode selection (directly on the graphic screen in a specific zone)

3.3.2 Structure of the HETI

The structure of the HETI is shown in Fig. 8. Throughout each task, the human operator has a number of options about the functioning modes of the system. Information about the state of the process is received, and the operator gets help, as needed, when the "help" mode is activated. A human operator model (concerned with possible human actions) is used. This model (along with fuzzy logic and fuzzy problem solving) comprises a fuzzy controller. In the event of human error, the fuzzy controller is designed to match the best operator strategy, which is correct: an efficient action is then applied to the (simulated) process.

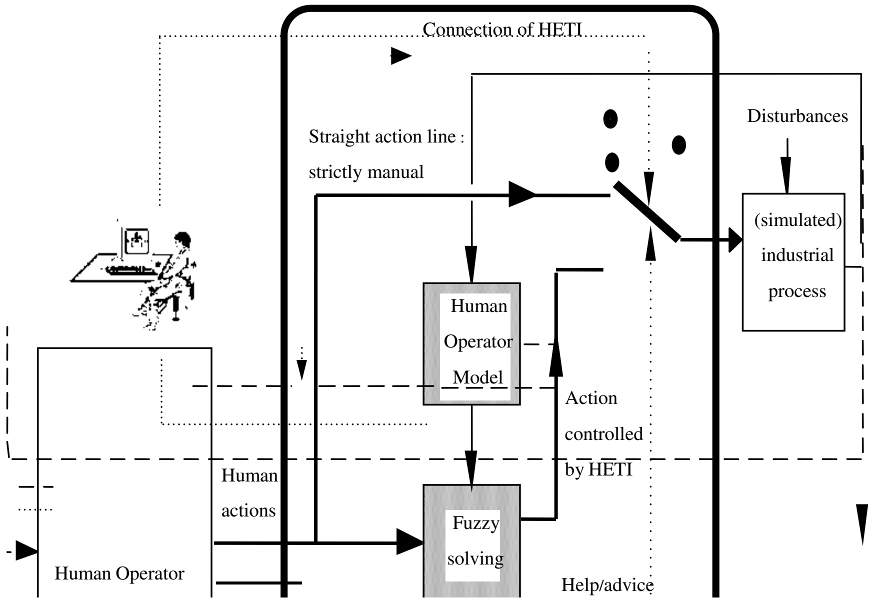

Fig. 8. HETI internal structure. The grey lines show the functioning mode options that the human operator may take. The dotted lines indicate the information output that can be used by the human operator. The bold lines show the input and the main outputs of the HETI. Finally, the fine lines show the processes mode within the HETI.

3.3.3 Description of the Human Operator Model

The temperature-adjusting operator performs the role of a temperature-control device which is responsible for keeping the hot water outlet temperature within a given range. Similarly, the fuzzy model of this human operator is the equivalent of a fuzzy controller. Fuzzy logic was selected for this model because it takes into account human imprecision and uncertainty. Moreover, it allows for descriptive modelling of knowledge and behaviour. The model's role in the HETI is: (1) to provide training to inexperienced human operators (during training, the right actions are shown to the human operator by the model); (2) to provide assistance to human operators in overload situations; in this case the model calculates the preferred course of action, which is then indicated to the human operator; (3) to assume control of the process when the operator is overwhelmed.

The fuzzy-logic reasoning controller selected here is similar to that designed by Sugeno and Nishida (1985); it allows direct output of the defuzzified control. Weights (W_i) are attributed to each rule (i). These weights are obtained from the premise of each rule. Every rule is systematically applied and used for control calculations. Fuzzification was performed using the simpler trapezoid function, to begin with. The rules and the fuzzy sets were determined according to five linguistic values: VN (very negative), N (negative), Z (zero), P (positive), VP (very positive). The fuzzy rules were set using the best operator's strategy. This operator's actions were used as a model for high-performance process control. In an ideal HETI, other (non-optimal) operator models must also be taken into account. In this case this operator's actions were observed during the temperature-adjustment task with thermal inertia, but without data deterioration. Indeed, preliminary testing has shown that the shortest possible procedures would give the best error-correction results from the HETI. A study of the operator's strategy highlighted two primary, logical principles. Whenever the hot water outlet temperature became higher than 30°C or lower than 20°C, the operator acted upon the number of in-use dispensers. However, if the temperature stayed within the desired range, the operator acted upon the cold-water inlet flow rate, which allows easier temperature control. This operator's strategy led to the design of five fuzzy rules, to be described in detail later.

The controller is composed of two fuzzy motors and one "strategy-choice device" (OCS) (Fig. 9), so as to use both temperature-adjustment strategies: (1) acting upon the dispensers, and (2) acting upon the cold-water inlet flow rate. The strategy-choice device compares the outgoing water temperature with a set value of 25°C, which corresponds to a mid-range temperature. This 25°C value was used for stabilising and optimising the temperature control.

Each fuzzy motor receives the $\Delta\tilde{E}$ fuzzy variables (variation of the error between the outgoing hot water temperature and the mid-range value of 25°C, over time) and $\tilde{E}$ (error between the mid-range value of 25°C and the outgoing hot water temperature of the process). However, only one of the motors selected by the OCS, does the controlling calculations. Motor #1 generates a flow-variation command, whereas Motor #2 generates a command to either add or remove a heat-exchanger.

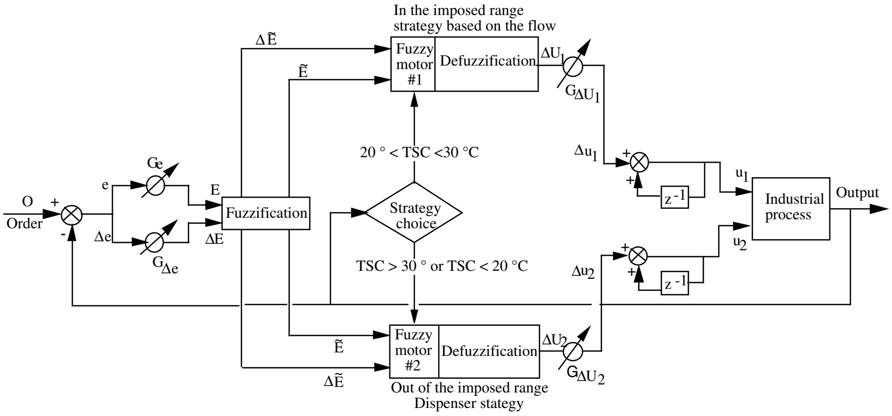

Fig. 9. Principle used for the fuzzy regulation with strategy choice (Beka Be Guema, 1994)

Fuzzification

The fuzzification of error and error variation was found using the best operator's strategy. This was done according to the five linguistic values introduced earlier (VN, N, Z, P and VP) (Fig. 10). The Z linguistic value corresponds to a membership function where a 0°C gap between 25°C and the outgoing water temperature gives an ordinate of 1. In the case of a 2.5 °C/s thermal inertia, for instance, error variation can really take only three values: -2.5°C/s, 0°C/s or +2.5°C/s, Fig. 10(b); these three values correspond to the possible rates of temperature variation within the hot-water outlet.

The five fuzzy rules can be placed in a matrix form (Fig. 11). For example, the rule yielding a very positive Δu command is the following: (if e is VN AND Δe is Z) OR (if e is VN AND Δe is N) THEN (Δu is VP).

A W_i weight, which is independent of the AND and OR fuzzy operators, is given to each "number i" rule (from 1 to 5). Weight calculation allows an estimation of the ratios in which the commands of each rule must be applied. The relative importance of each weight is related to the state of the parameters within the process to be regulated. W_i weight values are given by Guerra (1991):

$$W_i = \underset{\ell}{\mathrm{OR}}(\mathrm{AND}[\mu_{E_j}(e_0), \mu_{\Delta E_k}(\Delta e_0)]) \tag{1}$$

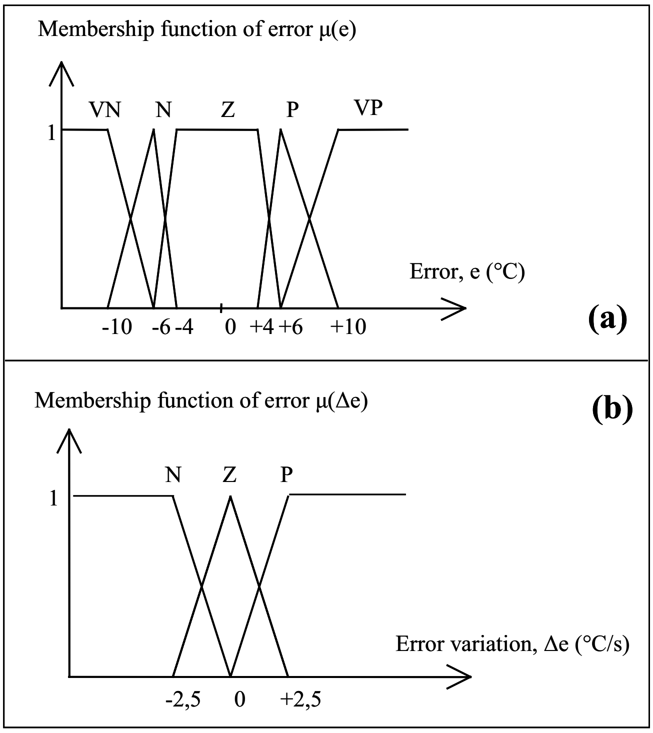

Fig. 10. (a) Membership functions of (a) error (the "no error" category (Z) was widened in order to avoid wobbling within the imposed range) and (b) error variation

e / Δe	VP	P	Z	N	**VN**
P	VN	Z	P	P	Z
Z	VN	N	Z	P	**VP**
N	N	N	N	-	**VP**

Fig. 11. Regulation rules matrix after adaptation.

where λ is an index that takes into account the number of entry combinations yielding the same Δu command (a Δu command is a command that is acceptable to the operative part, from the fuzzy command); k are indices for the linguistic variables that are taken into account, and $\mu_X(x_0)$ is the membership function of the fuzzy value to the X fuzzy set. The Min/Max logical functions are associated to the AND/OR functions:

$$\begin{aligned} \mathrm{AND}(\tilde{A}, \tilde{B}) &= \mathrm{Min}(\tilde{A}, \tilde{B}) \\ \mathrm{OR}(\tilde{A}, \tilde{B}) &= \mathrm{Max}(\tilde{A}, \tilde{B}) \end{aligned} \qquad (2)$$

The weighting formula (1) comes down to a "maximum of minima" calculation, and becomes:

$$W_i = \mathrm{Max}\left(\mathrm{Min}\left[\mu_{E_j}(e_0), \mu_{\Delta E_k}(\Delta e_0)\right]\right) \qquad (3)$$

Defuzzification

The controller output is obtained after calculating the weights of each rule. This can be done in many ways. If command variables Δu_i are set at the maximum of their linguistic values, two defuzzifications are possible (Buckley and Ying, 1991): linear and non-linear defuzzifications. Non-linear defuzzification was used here:

$$\Delta u = \sum_{i=1}^{n} W_i . \Delta u_i \Big/ \sum_{i=1}^{n} W_i \qquad (4)$$

where n is the number of rules (five in this case) and Δu_i are the maximum values of Δu for the flow rate and dispenser commands (Fig. 11).

Evaluation

The evaluation has been made in two stages.

During the first stage, several preliminary trials (without a human operator interacting with the HETI) have been performed in ways that validate the model technically. For the 20 temperature-adjustment sequences of the experimental protocol with thermal inertia, the model achieved the following performances: (1) for a 20/20 regulation performance, 20 acceptable adjustments were made over the 20 adjustments that had to be done; (2) during a change of input variables in the simulated process, the controller

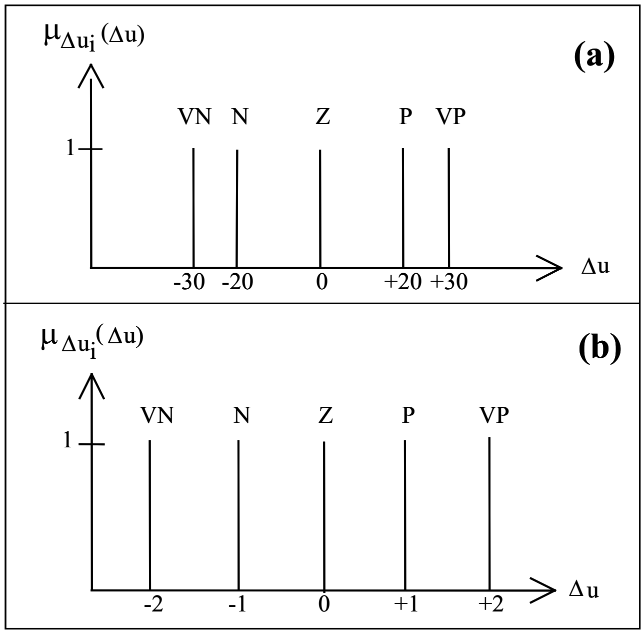

Fig. 12. Membership functions of Δu (a) for fuzzy motor #1: this fuzzy motor is used to control the inlet cold water flow. Control variables Δu_i are set at their maximum linguistic values. The arbitrarily set breakpoints are +20 and +30 for a flow-rate increase, and -20 and -30 for a flow-rate decrease. (b) for fuzzy motor #2: this motor is used to control dispensers d_1, d_2, d_3 and d4. The arbitrarily set breakpoints are +1 and +2 for an increase in the number of available dispensers, and -1 and -2 for a drop in that number.

reacts with a less-than-one second delay; (3) on average, a controller needs 3 s to find the next adjustment during each sequence change; this corresponds to the controlling program's execution time (Note that the very best human operator's execution time was 6 seconds on average, whereas the overall mean, including all subjects, was 12 seconds - the gap between the best operator's time and the controller execution time is due to the human operator's delayed reaction: 4 seconds on average); (4) the controller is stable throughout the 20 sequences; (5) a compromise was found so as to let the “strategy choice” device (Fig. 9) use the best operator's temperature-adjustment strategy while keeping the system stable.

During the second stage, an evaluation was done by five experts in human-machine systems (between 8 and 15 years of experience each in designing and evaluating such systems); they were all familiar with the research work being performed and the means being implemented. First, the experts were considered as human operators (subjects) interacting with the HETI during experiments in laboratory; in this case the aims were: (1) to check that, in situations when the HETI was in fact used, the expert's performance improved (even if it was *a priori* already proved during the preliminary trials); (2) to study their behaviour in relation to the HETI. During these experiments, the experts had to select the HETI option on the menu (Fig. 7) only if they considered it necessary; more the HETI was automatically activated when no temperature adjustment could be achieved within a predefinate period. The evaluation was performed using the double task (described in 3.2.2): after a trainig stage and simple tasks (see 3.2.1), the double task was done first without, and then with the HETI. In the double-task stages, the experts were required to complete the pentagon classification as a priority. The results obtained by these five experts are detailed in (Beka et al., 2000). They were very promising, showing the potential efficiency on such an intelligent interface approach.

These five experts were also considered as evaluators; in this case the aim was: to collect remarks and criticisms before and after the experiment, according to technical and ergonomic criteria (the principles of such classical evaluations are described by many authors, such as Nielsen (1993) or Wilson and Corlett (1996)).

4 Conclusion

Several different approaches are proposed in the intelligent human-computer interface domain, such as: flexible (or adaptable) interfaces, human-error-tolerant interfaces (HETI), adaptive interfaces, operator assistants (or intelligent operator assistants) or intelligent agents. Often, they combine technics and methods issued from artificial intelligence and human-computer interaction domains. In such approaches the modelling of the users and their objectives and tasks is very important: when the human tasks are complex, it is a difficult work for the designers, and a source of many imprecisions or uncertainties. In these conditions, fuzzy logic can be potentially very useful.

As an illustration, a human-error-tolerant interface based on fuzzy logic has been described in this chapter. The fuzzy-logic operator model was designed using an analysis of the best operator's actions after preliminary experiments. For the moment, this particular intelligent interface has been evaluated only in laboratory (with complex and representative human tasks): the first results are promising. A research and development perspective consists in adapting and evaluating this system in real situations in industry.

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