Information Technologies Based Questionnaire Tool in Human-Automation Systems

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Abstract: In this paper we present an Information Technologies (IT) based questionnaire tool in order to support evaluation activities related to industrial automation. We assess the questionnaire tool by giving special attention to teaching activities at different universities and industrial cooperation, all of them within the industrial automation field. In an initial assessment, the use of an evaluation questionnaire tool within an academic platform allows members from different universities to collaborate and to share knowledge. By means of an example, the Barcelona Tech University in Spain provides support for teaching activities in automation to the ESPE University in Quito, Ecuador. A second case study example is presented in order to show how to detect sources of complexity in human supervisory control room tasks in wastewater treatment plants. The first results show that the interface is effective, easy to use and understand and can help engineering students in a training program to play the role of control room operators and the elicitation of sources of complexity can be useful to improve the interaction between humans and safety-critical systems in the industrial domain.

Keywords: Display design, questionnaire, automation, supervisory control.

1. Introduction

Online learning communities are an effective approach of integrating collaboration in online learning environments [1, 2]. Yeh comments that "*online learning communities are a collaborative means of achieving shared creation and shared understanding in which mutual exchange between community members is encouraged to support individual and collective learning*" [3].

Nowadays, platforms based on information technologies (IT) for teaching purposes (teaching materials, videos, teaching guides, remote laboratories) are frequently used at Universities. For example, the Barcelona Tech University uses an adaptation of the Moodle Platform [4]. In this context, researchers such as Hsu et al [5] are working on the development of objective design criteria for web-based learning platforms. Furthermore, remote laboratories are a current complement in engineering education to provide remote access to experiments: "*the evolution of web technologies will benefit effectiveness of remote laboratories*" [6, 7].

However, to the best of our knowledge, examples of platforms in engineering education to study complex systems which integrate automation knowledge, human operator skills, information management and supervisory control are not found. This situation is due to the difficulty of having a realistic and low cost system available at the University.

Recent research works in human-automation in academic contexts have been focused on the use of role playing with engineering students and human supervisory control display design [8]. In these areas, integration between industrial informatics and Human-Computer Interaction (HCI) enables to improve the systems' performance. The role playing methodology can be useful in the management of complex systems, due to the fact that human supervisory task in control rooms requires team work and an effective management of abnormal situations. The use of guidelines and a human-centred approach [9] in supervisory control interface design can be useful in order to include ergonomic design considerations at the beginning of the system's design (trying to mitigate the mental workload, the human error adapting the difficulty of the task to humans or task allocation between humans and machines).

In order to support this interface design, effective evaluation tools are needed in order to comply with standards and to mitigate operator's performance problems due to perceived complexity issues. The major contribution of this paper is along these lines: to highlight the benefits of including IT to apply design guidelines by means of questionnaires. This enables to improve the interface at design phase by means of iterative evaluation.

Within the working context presented in this paper, it is of utmost importance to enable different collaboration schemes between Universities and Enterprises; as this allows experts to eventually hold face-to-face meetings and interviews or to work within a shared platform.

This paper presents the use of IT tools for evaluation purposes in order to allow different forms of collaboration and to reduce the effects of physical distance. In section two, we describe a set of evaluation questionnaire tools embedded in an IT based platform. These tools aim at contributing to remote collaboration between universities and industries in the field of industrial automation. Then, we assess the system in two case studies. In section three we present a first case study carried out in academic environments. The evaluation questionnaire tools are used by engineering students to design human supervisory control interfaces in a manufacturing system at the *Escuela Superior del Ejército*, ESPE University in Quito city (Ecuador) and teachers collaborate by using the educational platform, therefore showing its potential use for advanced educational purposes (always within the industrial automation field). A second case study example is presented in section four in industrial contexts. In this case, wastewater control room operators use a questionnaire of sources of complexity in order to help designers understand the perceived complexity and be able to develop effective supervisory control interfaces in wastewater treatment plants.

2. Questionnaires in Human-Automation Systems

In the industrial domain it is frequently required to study the system's degree of compliance with standards, codes of best practices or design and implementation guidelines. For instance, it is a usual practice before validating the order or delivery of the monitoring system interface design of the production facility (specified and developed by a supplier), that the manufacturer wish to analyze its compliance with the ANSI/HFES 200 Human Factors Engineering of Software User Interfaces [10]

In this case, prior self-evaluation of the degree of compliance with standards or guidelines can contribute to cost saving for the company. These savings are either direct, by optimizing investments to achieve better returns by improving the quality, or by saving time in correcting malfunctions in the already delivered deployments.

Moreover, not completing the certification or the need to stop temporarily the system in order to adjust the interface can be very damaging for the company.

One of the main difficulties for a company to self-evaluate compliance with standards and guidelines is the length and difficulty in interpreting and adapting standard definition documents to the specific situation of the company (standard definitions are usually very generic and need to be personalized). The company frequently requires the collaboration of an expert consultant to carry out an evaluation report. In other cases, the company will risk it and invest without prior audit, assuming the costs of future corrections.

The solution we propose to solve this problem is a tool with customized evaluation questionnaires. This tool offers the user (evaluator, designer, manager) standards, regulations, and guides. These documents are adapted and formatted in questionnaires so that answers are easily registered and assessed. According to the results of the evaluation, the system's improvements and evolution can be tracked and an action plan to correct malfunctions can be designed.

The main goal of this methodology is to facilitate expert documents such as standards, technical guides, best practice documents, etc., for non-expert users in evaluation projects. The tool allows non-experts to carry out evaluations without requiring a large investment in human and technological resources. There are two methods to obtain evaluation questionnaires for a particular project. First, we can import existing questionnaires such as customer satisfaction surveys from licensed, validated internet sources. Second, we can use the tool's edit options to create our own evaluation questionnaire.

The tool's functions allow collaborating online, focusing on industrial informatics and engineering areas by evaluating the questionnaires. These functions enable the implementation of continuous improvement quality projects. For instance, The *Historical Trend* function represents successive evaluations in a continuous improvement quality project context (see Table 1). The user has to understand, interpret and complete the questionnaire; therefore it has to be usable. The introduction of psychologists into the research and working group has helped to validate these questionnaires as an effective tool.

Automation is a critical field that becomes even more complex when human intervention is considered and, at the same time, where there is a lack of ergonomics and usability considerations when conceiving the control interfaces for human intervention (monitoring and supervision).

In the context of human-automation systems we have included two questionnaire prototypes into the system:

- GEDIS: ergonomic guideline for supervisory control interface design [11].
- Complexity questionnaire to manage complexity in an industrial control room: an adaptation of a questionnaire to manage complexity in nuclear power plant control rooms [12, 13].

In addition to these two initial evaluation questionnaires, other ones can be deployed.

The tool has been developed in PHP language [14] and supported by a MySQL database Server. In the response process, we use PHPAJAX Classes [15] to record and evaluate answers synchronously and instantly.

In what follows two case study examples are presented in order to show the potential application of such tools.

3. Case Study: ESPE Project

This is a case study based on the academic cooperation between universities: the role of each University complements the other.

The Department of Electrical and Electronics at ESPE University, in Quito (Ecuador), teaches in the control and automation field. The practical work takes place in the laboratory using a training system called CIM-2000 Mechatronics [16]. This training system is a modular manufacturing system, which provides methods, techniques and facilities to train and exercise the implementation of the CIM concept "Computer Integrated Manufacturing".

The manufacturing system has several stations and tools: PC Based control station; closed loop conveyor system; automatic storage and retrieval station (*Store*); two manufacturing stations with Computed Numerical Control (CNC) machines and handling robots (*CIM*); Hydraulic and Pneumatics stations; Programmable Logic Controllers (PLC); data communication network and Supervisory control and data acquisition software. From the initial meetings between ESPE, UGIVIA, EPSEVG and UAB university teachers, to establish the collaboration between the members, we highlight the following considerations.

Context of use

ESPE students take the role of maintenance, control and supervision operators. The ESPE teacher and the Spanish members take the roles of project manager and supervisors. The methodology used is Problem based Learning (PBL) and role-playing where the group of students learns to develop different roles throughout the project. Tasks are divided into sub-projects:

- Learning the system and system configuration
- Implementation of the LAN network
- Development of Human Machine interfaces
- Development and implementation of the database
- Implementation of the monitoring system

Each academic year the overall project is divided into these five sub-projects and the student groups have 4 months to develop the project. In each sub-project the objectives and requirements are defined and students have to program and start-up the stations. Moreover, students have to develop detailed technical documentation of the work. Through previous face-to-face meetings between the authors and the ESPE teacher in the year 2010 in Spain, a set of requirements were detected to be considered in the early stages of the project development:

- Due to the ESPE teacher's experience in the management of the manufacturing system, it is possible to jump from automation towards human supervision, which enables the collaboration between universities.

– A current step is the design of the monitoring interface of each station and the global interface system according to guidelines based on HCI knowledge and techniques.

Procedure

The schedule of collaboration activities between the members of the universities during the semester course is as follows:

– Starting point: First human machine interface, HMI, prototype of the manufacturing system prepared by students (from March to July 2010)

– Delivery of the prototype to Spanish members. Apply the GEDIS guide to this prototype. Publish comments using the online version of the guide, where teachers in Ecuador can see the initial assessment and the aspects to be improved (September 2010).

– Write a detailed report using the online tool (September 2010).

– Discuss improvement aspects (September 2010). Students of the current academic year prepared a second HMI prototype (See Figure 1). In this case, students use the GEDIS recommendations from the beginning (from October 2010 to February 2011).

– Delivery of the prototype to Spanish members. Prototype evaluation (March 2011).

– Write final report (March 2011).

Prototype evaluation

The evaluation of the developed prototype SCADA monitoring interface was performed by applying the GEDIS guide implemented in the questionnaire tool. The GEDIS guide has a total of ten indicators that enables to characterize the interface: structure, distribution, navigation, color, text, device status, process values, trend graphs, commands, data entry and alarm system (see Table 1). The weighted sum, with all the indicators with equal weight, gives a value of 2.4 for prototype P1 (September 2010) and a value of 4.27 for prototype P2 (March 2011) on a numerical scale from 0 to 5. Improvement from the first prototype has occurred in nine of the ten indicators: Indicator Trend graphs in the assessment remain the same (besides being a high 3.5 rating on a scale of 0 to 5). The 40 screens making up the SCADA have been improved and revised. The basic aspects that have been improved regarding the first prototype are:

– Structure and navigation of the application.

– Objects’ distribution on screen

– Use of color and text

The most relevant aspects that have been improved are:

– The manufacturing system is a sequential

Figure 1. Second HMI CIM 2000 prototype using the GEDIS guideline. In this screen the user has a clear situation awareness (alarm information at the top) and a good access to alarms window or levels of automation (manual control, automatic control)

set of operations (transfer, machining, handling, etc.). This sequential order did not correspond with the presentation of the stations in the interface. The presentation of the menu bar was improved in order to access station screens from left to right, and a second menu bar was created using keyboard shortcuts to features that added clarity and understanding on how to handle the interface.

– In the display, human operator intervention was not clear as there was some confusion in distinguishing the automatic, semiautomatic and manual mode. By conveniently regrouping the modes and using symbols and icons in a better way, it was possible to standardize user intervention at the interface

– The visibility and location of the alarm system in the interface was hidden by several layers of navigation. The understanding of the risk perception was improved, along with visibility of alarm indicators; and a shortcut to the alarm display and more direct user recognition was added, preventing the user from remembering how to access the information.

Thus, by applying the GEDIS we have simplified the complexity of the interface, making it more understandable and easier to use.

Performance evaluation

From the point of view of analyzing the system's performance, the first proposed assessment is to evaluate effectiveness (success in task development), efficiency (time and resources required) and satisfaction (subjective assessment). A population of nineteen engineering students has been used to evaluate the following objectives:

1. Full integration of all stations through a LAN network.
2. HMI design of the system, developed with a SCADA package
3. A database system with structural data
4. A reporting system for analysis and statistics.

Based on these objectives the results are summarized in Table 2. The results shown in Table 2 indicate the fulfilment of Goals 2 and 4, and a 50% compliance with Objective 1 as it was not possible to achieve an efficient integrated operation between stations in the laboratory. Objective 3 needs to be improved in future studies and it is necessary to develop a database server and a database such as InSQL.

To analyze the goals, we studied a set of parameters, starting with functionality (F), interface design (ID), quality programming (Prog) and technical documentation (P) (see Table 3). Task development assigned to different groups required an investment of around 160 hours per group, distributed over a two month period, but this turned out to be too short to meet all the objectives, and required better time distribution, and major student involvement.

At this point it is necessary to remark that although students have sufficient prior technical knowledge to start the project, they must integrate this knowledge and manifest the skills acquired in order to complete the tasks successfully.

In the management of complex systems, the number of variables involved (changes and improvements in the programs, tasks to be changed to improve devices that need maintenance, coordination between group members) and the maturity to move from novice to expert involve the qualitative information of Table 3, in which different characteristics are seen in the projects carried out.

Satisfaction evaluation

Finally, the Spanish members prepared a satisfaction questionnaire to assess the use of the online questionnaire (a Likert scale with four answers). In this questionnaire, the ESPE teacher evaluated that the quality of the first prototype P1 developed by the students was poor. In addition, the task with the interface was long, required concentration and they felt time pressure. Regarding the online application of the GEDIS guide, the ESPE teacher appreciated the GEDIS questionnaire as it was easy to understand, but the changes from prototype P1 to a second improved version (P2) involved a large task and although the quality of the online tool was fair, it would require being able to provide more detailed explanations whether an indicator of the guide requires a redesign or minor or profound retouching. In the final documentation supplied from Spain on the GEDIS guide regarding the interface of the manufacturing system, the ESPE teacher indicated that the quality was good. Finally, in assessing academic collaboration between universities, the ESPE teacher assessed that it was acceptable, but it could be improved to carry out collaborative tasks more continuously and not only in particular moments of the development.

4. Case Study: Complexity Sources

This is a case study based in the academic-industry cooperation between universities and an expert human supervisor in control room of a waste water treatment plant. The main goal is the identification of sources of complexity in plant supervision, as an important amount of information and measures are present [18]. Complexity in plant control rooms can be explained objectively and subjectively. Objective complexity is associated with the automated system. One approach to investigate the objective sources of complexity in control room environments is to study and analyze real world incidents. Alternatively, subjective complexity is related to human perception and the way the human process perceives information [12].

Context of Use

The scope of the tasks is within the industrial domain (energy, oil, petroleum, wastewater, etc.). In the Industrial-academic approach, the role of the University is as a designer [17] and implementer and the role of the company is as a customer. The context of use is the study of complex systems, focusing our attention on the identification of sources of complexity. Following the words of Xing [12]: *a questionnaire can be used to determine when the complexity of a display is beyond the operator's capacity limits of information processing, thus, the display is unacceptable for efficient and safe operation".* Therefore our interest focuses on automating and facilitating, as much as possible, the application of such questionnaires.

Procedure

We have adapted a complexity source questionnaire aiming at managing complexity in an industrial control room [12].

The original questionnaire of sources of complexity has six complexity source categories: physical environment, task factors, procedural factors, organizational factors, human-system interface and cognitive factors. The questionnaire has 84 questions. In the human-system interface, the objective is to assess the components of the control room with which operators must interact in order to control, monitor and interact with the system.

Professionals from a usability laboratory together with an expert in industrial supervision and maintenance collaborated to adapt the complexity source questionnaire to manage complexity in an industrial control room. In our prototype we are trying to improve the grouping of the questions in categories, creating an online questionnaire. In an initial approach, the end-users are human supervisory control room operators in wastewater treatment plants (WWTPs). There are three operators who carry out human supervisory tasks inside the control room in three Spanish WWTPs [19]. The first step in our collaborative work is the development of WWTP interfaces using SCADA software and taking operator assessment into account in order to obtain effective displays. The schedule of the collaboration is as follows:

- Adaptation of the original questionnaire of sources of complexity into a Spanish version (December 2010)
- Design of an online complexity source questionnaire (January 2011)
- Test with three WWTP Spanish control room operators (April 2011)
- Develop heuristics and recommendations in order to improve a WWTP supervisory control interface (October 2011)
- Prototype design of an effective WWTP display (2012)

Performance Evaluation

The questionnaire is a 5-point Likert scale (from strongly disagree (1) to strongly agree (5)). As examples of questions and recommendations: in the question "The displays use too many different fonts", user1 gives a score of 3, user2 of 3 and user3 of 2. A good recommendation is to review the number of fonts on the screen. As a second example, in the question "I don't have to access too many displays to perform a specific task", user1 gives a score of 2, user2 of 2 and user3 of 5. A good recommendation is to review the architecture of the interface and create an accessible navigation bar.

In the original questionnaire of sources of complexity there are open questions. For example: "How complex is your job? What makes it complex or not?” In this question user1 assessed that the complexity level was low, user2 assessed that the complexity level was medium and user3 assessed that the complexity level was low. The user2 has three years of experience while user1 and user3 have ten years of experience. Unlike a nuclear power plant, real incidents are less frequent, however from the responses of the operators abnormal situation management is a critical factor in their work. A polar diagram can help us to identify answers with low qualification (strongly disagree is a minimum on Figure 2). In the global assessment of the user3, important factors are the physical interaction with the environment and with the other operators in the control room. With the use of an open dialog box, the questionnaire tool allows the user to explain these facts. The user3 shows that screens are easy to access, however it is necessary to configure a great number of parameters. From the point of view of the physical interaction, this user highlights the great effort to attend the maintenance of devices (secondary task) and in some occasions he loses the concentration in supervisory tasks (primary task). In some occasions this user feels overwhelmed by the amount of interaction with other operators required by the system. Due to the results of the complexity questionnaire, we have acknowledged the necessity of improving some heuristics such as: fonts, architecture and navigation.

Prototype design

With the end-users answers, and with the help of the GEDIS guideline, is possible to create new effective interfaces aiming at minimizing the user perceived complexity. For this reason we are working in the creation of new WWTP interfaces prototypes. In this subsection we present briefly this effort.

Our prototype includes: the WWTP process simulated interface, the controller program description, the SCADA interface application and finally the equipment failure in order to add industrial realism (these faults affect the dynamics of the plant and the operator’s behaviour).

In our approach, we are working together with an expert operator. The previous mentioned user3 has ten years of experience in this domain and he is working in the development of a WWTP effective display.

Following the GEDIS guideline, in our prototype there is a limitation in the number of different fonts used (maximum 4 fonts). There is an accessible navigation bar (bottom) in order to move through the areas of the WWTP. There is a graphical bar (top) in order to allow the operator to easily identify an alarm in a promptly manner. From the alarm manager of this SCADA, using script programming in the SCADA and object oriented programming in the PLC controller; it is possible to simplify the connection between the alarm warning on the

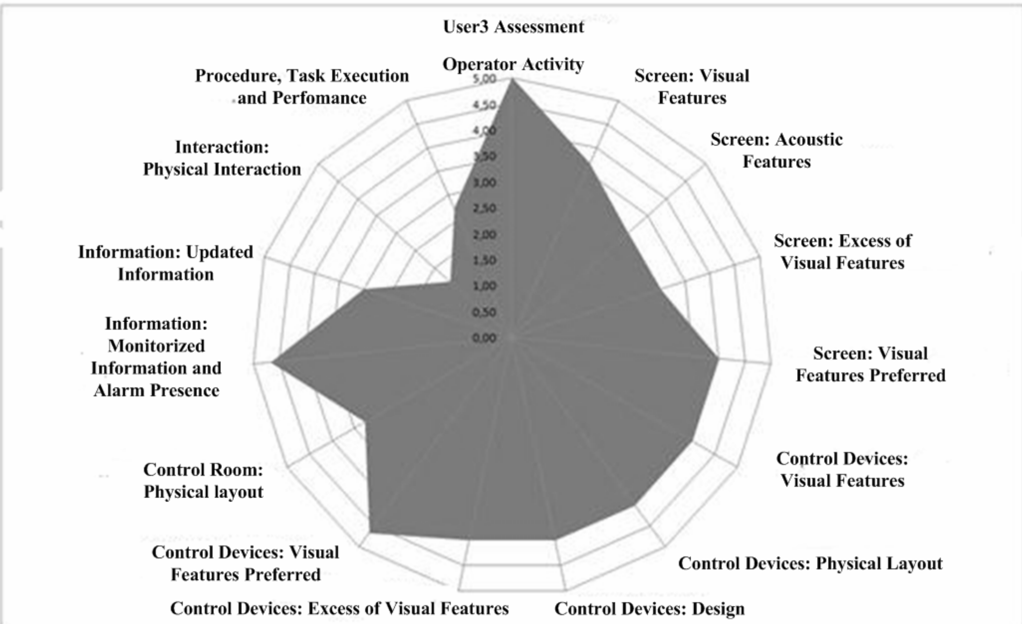

Figure 2. User3 global assessment of complexity sources

screen and the diagnosis of an abnormal situation in the plant. A diagram of the elevation and grinding process SCADA screen is shown in Figure 3. The elevation process consists of 5 screw pumps that feed the tank of water with three contributions, each of different effluents. The elevated flow chamber reaches a deal that delivers water from 3 grit lines, each equipped with a coarse sieve and a fine one. This emulated process is realistic taking into account the Spanish WWTP near the authors' region.

necessary to improve academic collaboration, but we highlight that this tool allows us to efficiently record tasks, processes, reviews, comments and final reports for a later analysis of the data. The knowledge transfer in project management and interface design was easier using the tool. From this point on, we hope that the skills acquired will be consolidated in student and teacher activities at ESPE University. Regarding the industrial-academic cooperation we have the ability to transfer

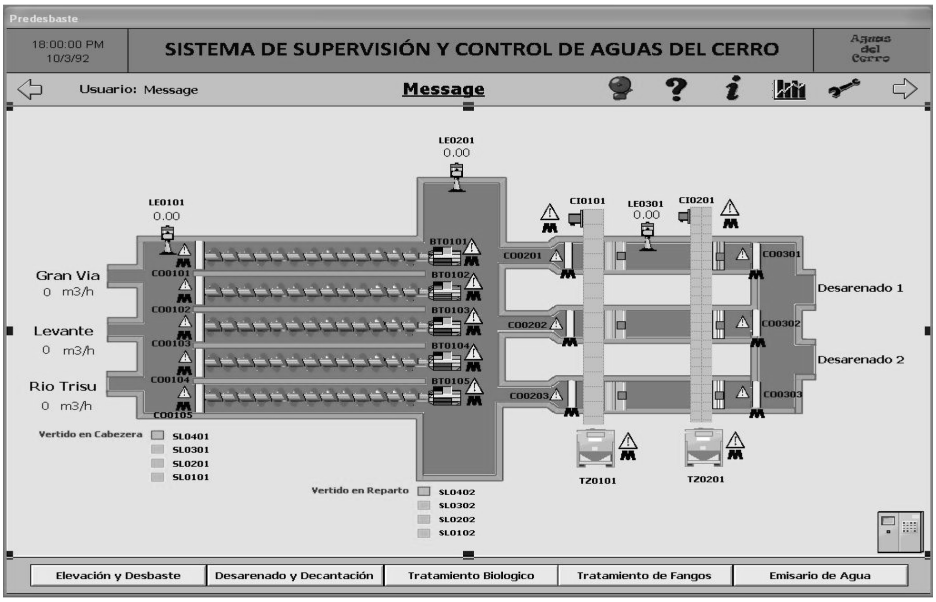

Figure 3. A prototype of a SCADA interface for WWTP environments. In the design of this WWTP prototype we have reduced the plant complexity into a clear and intuitive interface, easy to use, through the GEDIS guideline.

5. Conclusions

Our experience in implementing role playing and PBL methodologies has shown us the need to develop tools that facilitate the exchange of knowledge and experience. We started using a printed version of the GEDIS guide and then considered the development of an electronic, online version. Through an online evaluation tool it is easier to modify and update the content and include several user profiles. The programming tool is flexible in the sense that it is easy to adapt and create new questionnaires. This allowed us to invite external users to participate in the use of the tool. The use of the tool enabled us to share teaching experiences. While automation tasks were developed in the teaching laboratory at ESPE University, from Spain we gave support in the effective design of the supervisory control interface. It is still knowledge. By using our evaluation questionnaire tool it is easy to obtain a qualitative comparison between users' answers and allows us to prepare a set of actions in order to reduce the complexity in human-automation interaction.

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Annex

Table 1. Two successive evaluations using the GEDIS guideline: prototype P1(September 2010) and prototype P2. Detailed evaluation of the CIM case study in the application of the GEDIS guideline. With our evaluation tool is possible to identify the indicator that can be improved (grey dark circle), the indicator correct (grey clear circle) and the optimum indicator (mark).

	Capítol	nºR	nºC	nºO	aval	ev	nºR	nºC	nºO	aval	ev
1	Estructura	3	3		2.7	→	3	3		5	↑
2	Distribución	3	3		2.7	→	3	3		5	↑
3	Navegación	2	2		3	→	2	2		5	↑
4	Color	5	5		2.2	→	5	5		4.6	↑
5	Texto	4	4		0.8	→	4	4		2.5	↑
6	Estado de los dispositivos	2	2		1.5	→	2	2		4	↑
7	Valores de proceso	2	2		3	→	2	2		5	↑
8	Graficos y Tablas	4	4		3.5	→	4	4		3.5	→
9	Comandos de Entrada de Datos	3	3		3.7	→	3	3		5	↑
10	Alarmas	5	5		1.6	→	5	5		4.2	↑
	Global:	33	33		2.36	→	33	33		4.27	↑

1	**Architecture**	
1.1.1.1	Map existence	✓
1.1.1.2	Number of levels (le)	●
1.1.1.3	Division: plant, area, subarea, team	✓
2	**Distribution**	
2.1.1.1	Model comparison	○
2.1.1.2	Flow Process	●
2.1.1.3	Density	●
3	**Navigation**	
3.1.1.1	Relationship with architecture	○
3.1.1.2	Navigation between screens	○
4	**Color**	
4.1.1.1	Absence of non appropiate combinations	✓
4.1.1.2	Color number (c)	✓
4.1.1.3	Blink absence (no alarm situation)	✓
4.1.1.4	Contrast screen versus graphical objects	✓
4.1.1.5	Relationship with text	✓

Table 2. Case study ESPE Project Objectives and Results

Obj.	CIM	Pneum	Store	Control	Vision	Rob
1	50%	50%	50%	50%	50%	50%
2	100%	100%	100%	100%	100%	100%
3	80%	80%	80%	80%	80%	80%
4	100%	100%	100%	100%	100%	100%

Obj: Objectives, Stations: CIM, Pneum: Penumatics, Store, Control, Vision, Rob: Robotics

Table 3. Case study ESPE project. Characteristics

Obj.	CIM	Pneum	Store	Control	Vision	Rob
F	Accept	Good	Good	Good	Accept	Good
ID	Good	Good	Good	Good	Good	Good
P	Accept	Accept	Accept	Accept	Accept	Accept
Prog	Accept	Good	Good	Good	Accept	Good

F: Functioning; ID: Interface Design; P: Porfolio; Prog: Programming, Accept: Acceptable; CIM: Main station; Pneum: Pneumatic station; Store: Store station; Control: Control station; Vision: Quality station; Rob: Robotic station