Int. J. Engng Ed. Vol. 18, No. 3, pp. 357–368, 2002
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Design-for-Safety Competencies for Automated-System Design Engineers: A Case Study*

FRANÇOIS GAUTHIER
Industrial Engineering Department, School of Engineering, Université du Québec à Trois-Rivières, C.P. 500 Trois-Rivières (Québec), G9A 5H7, Canada. E-mail: francois_gauthier@uqtr.uquebec.ca

RENÉ BENOÎT
Institut de Recherche en Santé et en Sécurité du Travail du Québec, 505 boul. de Maisonneuve Ouest, Montréal (Québec), H3A 3C2, Canada

Since the 1960s, the use of programmable technologies has been constantly evolving in all facets of paper production. However, production system automation is responsible for a certain number of serious accidents. This article first presents the current situation in design practices for automated facilities, based on data collected in twelve paper mills from semi-structured interviews and focus groups. Eight competencies that design engineers in large processing industries should have so that they can better apply worker safety considerations when designing automated systems are then presented. These competencies were the basis for an extensive training program for automated-system design engineers.

INTRODUCTION

PRODUCTION AUTOMATION has enabled manufacturing companies to increase their productivity and replace the human operator in what are sometimes hazardous tasks. In the pulp and paper industry, the integration of programmable technologies began in the 1960s. Since that time, there has been a constant evolution in the use of these technologies in all facets of paper production. However, production automation has not been a miracle solution to the occupational safety problems involving the equipment used in paper mills. These companies' production systems are constantly evolving and control systems are regularly being designed, renovated and modified, which has a significant impact on worker safety. As a result, automation is responsible for some serious accidents occurring in these plants.

Literature review

Recent literature on machine safety reports a growing concern about the risks associated with new production technologies. Several studies have focused on accidents involving automated production systems that use programmable technologies such as programmable controllers and distributed control systems [1–5]. It has been observed that new hazardous phenomena have been introduced with these new technologies. Consequently, the idea that automation would eliminate all accident risks by removing the person from the danger zone has now been rejected [6]. By analyzing the general conclusions of several recent studies, Doucet [7] has noted that:

1. accidents occurring on automated sites are often serious;
2. accidents frequently occur in automatic operating mode during or following human intervention (repairs, adjustments, maintenance, etc.); and
3. protective devices, when they exist, are often ineffective, mainly due to deficient design.

Consequently, although there are several benefits in automation (increased productivity, reduced costs, better working conditions, etc.), the fact remains that new hazardous phenomena have been introduced with these technologies, and specific measures need to be taken to avoid the incidents that can result from them [8]. Today, the designer's challenge is therefore to design automated systems that are more flexible but that also offer a higher level of safety for workers.

Problem and research objectives

Some serious accidents attributable to automated equipment have prompted the pulp and paper industry to question the safety of automated systems, considering their complexity. These questions prompted a group of pulp and paper plants to ask the Institut de Recherche en Santé et en Sécurité du Travail du Québec (IRSST; Quebec Occupational Health and Safety Research Institute) to study this problem. The IRSST initiated a preliminary project to establish the causes as well

* Accepted 24 July 2001.

as the extent of the problem. Although this question appeared to be relatively simple, it required the direct and simultaneous collaboration of numerous disciplines. What seemed at the start to be only a problem involving equipment lockout procedures rapidly emerged as the symptom of a much bigger problem. The researchers, in fact, noted that the very design of the automated systems was often deficient with respect to safety.

A major research project was then developed, with the ultimate objective of significantly improving the safety of automated facilities, not only in paper mills, but eventually in many other large-scale processing industries. However, considering that various complex situations exist in these plants, that several technical, operating, maintenance and management disciplines are involved, and, finally, that there is a relatively rapid evolution in components and systems, the researchers soon realized that proposing technical solutions would not achieve the desired objective. Specific solutions to these sporadic problems would only be stopgap measures in an evolving situation.

The researchers then directed their attention towards a more permanent and more prevalent solution: increasing the design engineers' expertise in the efficient design for safety of automated systems. This involves much more than the simple acquisition of new knowledge by the design engineers. To design more efficient and safer production systems that are better adapted to the reality of operators and maintenance personnel, designers must develop to a greater degree certain specific competencies that allow them to efficiently mobilize all pertinent knowledge. The solution favored by the research team was therefore to develop a training program based on a transfer of competencies and intended for all engineers involved in the design of automated facilities in large processing industries.

The research project was to achieve, chronologically, three specific objectives: (1) to determine the nature of the safety problems encountered by workers in these industries and their origins or links to design activities; (2) to explicitly define the design process used by the engineers in order to integrate design-for-safety activities; (3) to develop a continuous training program based on a transfer of competencies that is consistent with the main structures of the design process established from the engineers' practice and that ensures that safety is taken into account right from the start of the design process.

This article focuses on one important aspect of the third objective of this research: defining the competencies that should be developed and that would be the basis for the training program. A competency is a complex and skilled knowledge base, requiring the simultaneous consideration of knowledge, ability and behavior or attitudes. A competency therefore consists of theoretical knowledge (what?), procedural knowledge (how?), and conditional knowledge (when? and why?). Once developed, competencies allow problems within a class of situations not only to be identified, but also to be solved efficiently [9]. While traditional training programs focus on the acquisition of theoretical knowledge, a training program based on the transfer of competencies puts much more emphasis on conditional and procedural knowledge. Its main advantage is to ensure that the acquired knowledge can be put into practice more rapidly and much more autonomously. A competency-based training program requires the integration of knowledge and is therefore more consistent with the engineers' professional reality [10].

METHODOLOGY

A multidisciplinary research team was created that consisted of a dozen specialists/researchers from various complementary fields of expertise: machine safety, design, automation, ergonomics, training and communication. A majority of the researchers in the team were experienced engineers.

In order to identify the competencies required to ensure a better integration of safety right from the start of the design process, the context in which these competencies would be integrated had to be well understood. In their approach and methodology, the researchers focused on a better understanding of industrial reality by getting as close as possible to the actual work site, while developing the necessary trust for effective communication with the participants involved. The researchers therefore had to collect a large number of data in order to properly understand the automated-facility design process, the involvement of the various participants, the integration of safety aspects, and the deficiencies inherent in all of these activities.

Twelve of the 56 largest plants in the Quebec pulp and paper industry were visited in the context of the project. Each of the visits involved lengthy planning and generally lasted three days. The majority of the research team members actively participated in collecting and analyzing data during these visits, which were spread out over a period of 14 months. During the visits, several people involved in the safety aspects of the automated facilities were met and observations were made on site in the case of operators and maintenance people. In this context, the researchers not only had access to the opinions of the various groups of people involved, but they also had the opportunity to learn about hazardous situations and the risks inherent in the automated facilities. Semi-structured interviews were also conducted with project engineers, process engineers, control and instrumentation engineers, middle and senior managers, health and safety managers, and operators and maintenance personnel for the automated systems. Abundant documentation was finally collected and analyzed.

In addition to the plant visits, focus groups were also met including representatives of various groups of participants involved in the safety of automated facilities (engineers, operators, maintenance personnel, health and safety managers), in order to discuss the differences in experience and in the ideas of each of these groups. Finally, since automated systems are, to a large extent, designed by outside engineering firms, design engineers from the main consulting firms were also interviewed.

A picture of the design practices for automated facilities was developed from data collected during the visits, from semi-structured interviews and from the focus groups. The needs, problems and phenomena observed were analyzed in detail and the research team identified the competencies that would be the basis for the training program. Since the methodology adopted was of the research–development type, the conclusions from the study were regularly validated with the different players in the pulp and paper industry in an iterative process. Fig. 1, which summarizes the research methodology, shows this validation process.

The conclusions were periodically subjected to the critical eye of the participating industries' representatives in two committees responsible for providing follow-up to the research; namely, an advisory committee and a technical advisory committee. The advisory committee consisted of joint sector representatives (workers and employers) from six paper mills, and representatives from the Association pour la Santé et la Sécurité des Pâtes et Papiers du Québec (Quebec Pulp and Paper Health and Safety Association). They were to give their opinions on the study's orientations as well as on result validation and adoption by the industry as the project progressed. The purpose of the technical advisory committee, consisting of expert engineers mainly from this milieu, was to facilitate more detailed exchanges on the scientific and technical aspects of the research.

RESULTS

The main findings on current design practices

International occupational health and safety policies promote the elimination at source of machine-related risks. The design phase is therefore essential for integrating safety into tools, machines and industrial production systems [11]. This integration is even more important with very complex systems, such as automated systems. An analysis of the data collected revealed that the practices in the mills visited did not efficiently promote the elimination of hazards at source by integrating safety aspects during design. The following paragraphs present the research project's

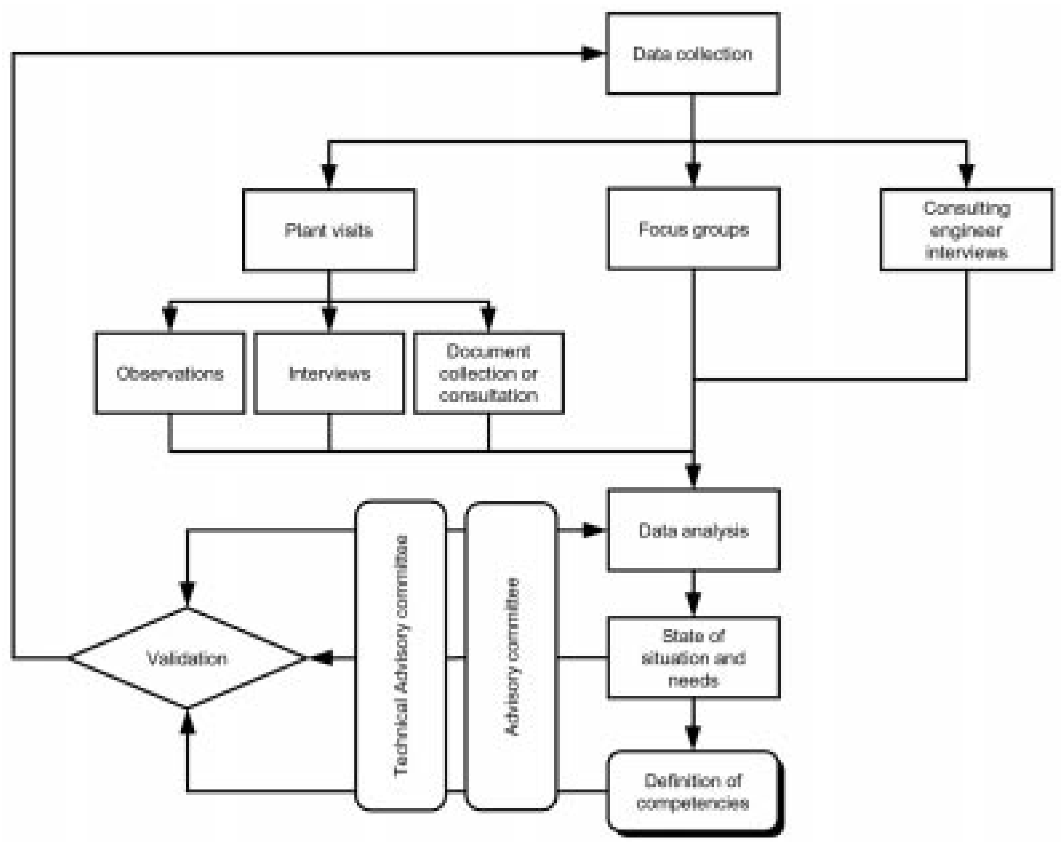

Fig. 1. Research methodology.

main findings regarding automated-facility design practices.

The automated-facility design process. Although most of the people interviewed consider worker safety to be important, they are not always successful in integrating it into design. The temporal, functional and financial aspects tend to occupy their attention. As a result, safety is most often dealt with through verification and review activities which are isolated from the design process (*a posteriori* verification of compliance with standards, use of checklists, safety reviews, etc.).

Another significant finding is that automated-facility design and modification are not based on any defined and formal process. Although a common process seemed to emerge from one plant to the next, this is based to a great extent on the experience of the people on site. In most of the mills investigated, practically no documentation existed on the design process or on the approach to be used in carrying out a project. In addition, the researchers observed no real effort to systematize design activities. Lack of a systematic design process seems to be one of the main reasons for the failure to integrate safety and design. Without an explicitly defined design process, design engineers have difficulty effectively integrating safety-related activities.

User-needs analysis. Identification of the 'clients' or users of a system and research on and analysis of their needs at the time of design have an important impact on the system's level of safety once it is in operation. The researchers noted that the design engineers do not employ a systematic user-needs research and analysis approach. Although operating and maintenance personnel are occasionally consulted, both the engineers and workers consider this process to be frustrating. When the project is at the detailed design stage, the designers show the drawings and control diagrams to the operators and the various maintenance personnel, asking their opinions. Even when these engineering documents are understood by the workers, which is not always the case, they provide very little information about how the personnel will interact with the automated system. At this stage, the workers often feel excluded from the process: they are offered an almost finished product and they have difficulty imagining what effect it will actually have on them in their work [12]. This results in considerable difficulty in obtaining pertinent information, and lack of time is generally given as the reason for not carrying out this crucial step.

Communication and teamwork. The design or modification of automated facilities generally involves managers, project engineers (from the plant or head office), process engineers, instrumentation and control technicians and engineers, consultants and other subcontractors, as well as operations managers. The conclusion from the interviews conducted with these different groups of people was that some automated-system design or modification projects have suffered from certain difficulties related to lack of collaboration between the different disciplines. For example, the research team identified many instances of lack of coordination and cooperation in identifying needs and analyzing risks. Communication problems between the different participants were also noted during this study. The philosophy of traditional sequential engineering is better known than that of concurrent engineering, even if some activities are carried out in parallel. These deficiencies in communication and in the ability to work closely in multidisciplinary teams directly affect the design engineers' ability to effectively incorporate safety aspects into the design process.

Risk analysis. The researchers noted that the engineers and other people involved in design did not know or had not mastered existing risk analysis methods (failure mode and effect analysis, fault tree analysis, hazard and operability study, etc.). They therefore do not use these methods extensively. The reasons given are mainly lack of time and lack of the necessary knowledge for their application. Although some examples of the use of the Hazard and Operability Study (HAZOP), What-if Analysis, and checklists have been documented, they were not applied to design aspects but rather to subsequent analyses of already operating systems.

The use of safety technologies. Despite the problems observed in the methodological and organizational aspects of design, observations made during the study revealed that the North American state-of-the-art approach to control system safety is generally respected. Nevertheless, certain deficiencies were observed, namely in safety functions and devices (interlocking, emergency stops, use of devices developed for process monitoring in order to fulfill a personal safety function, ease of program modification, etc.). These control-system design inadequacies may result in a series of events or machine interventions that expose workers to a high risk of serious accidents. Outside the debate surrounding the reliability–safety equation for programmable technologies, the fact remains that the choice of technologies as well as their arrangement may have a considerable impact on a system's safety. Furthermore, the Quebec pulp and paper industry has expressed a desire for significant improvements to be made at this level.

Competencies identified

These findings indicate that there is a major difference between the current practices of automated production system design and those that would allow safety to be better taken into account. The data and observations gathered and analyzed jointly by the multidisciplinary team members indicated several needs that should be met by design engineers, and these pointed towards the necessity of improving eight competencies directly related to their design process. The eight competencies identified are: (1) the use of an efficient design methodology; (2) needs analysis; (3) the application of safety technologies; (4) risk management; (5) teamwork; (6) communication; (7) ethics and professionalism; and (8) promotion of this approach. These competencies were the subject of two validation sessions with the technical advisory committee members. Each validation session led to a review, if necessary. The following subsections present the reasons for choosing each of the competencies in relation to the previously identified needs, as well as the main sub-competencies related to each.

Efficient design methodology. According to most researchers and professionals, safety must be incorporated into all design activities throughout the design process in order for it to be effectively integrated into machines [13–16]. A design process is the systematic progression of activities necessary to produce a product, a tool or a production system. In such a process, all the activities, required resources and their organization are explicitly defined. Fig. 2 schematically illustrates the integration of safety aspects throughout the design process. This study has shown that the design and modification of automated facilities in large processing industries is not based on any defined and formal methodology. There is very little documentation on the design process itself, thus making it almost impossible to systematize or optimize the activities, and consequently, to integrate safety aspects into the process. There is no lack in motivation for safety, only in its effective integration into design.

As a result, the first competency that should be further developed by the design engineers is the development and application of a methodology, a systematic design process that simultaneously integrates all design considerations as well as the functional, financial and temporal aspects. This competency includes design validation aspects, mainly from the standpoint of safety throughout the process, primarily through formal safety reviews. It also includes the application of pertinent standards and regulations, the integration of safety technologies into design, and the production of appropriate design-related documentation.

In Fig. 3, which shows the interrelationship between the eight competencies, this competency is shown as the core of the training program. This choice is based on the fact that, in the 'real' life of engineers responsible for automated-system design, an efficient design process or methodology must encompass needs analysis, the choice of safety technologies, and risk management. Such a design process also requires functional teamwork methods and appropriate communication strategies that are in keeping with the philosophy of concurrent engineering. It requires as well that engineers assume a high degree of professionalism and that, to a certain extent, they be responsible for promoting safety to operators and maintenance people as well as to the company's managers, right from the start of automated-system design in their workplace. In the dynamics of the training program, this competency will therefore manage the entire organization of the program components and training activities.

User needs analysis

One of the very first steps in the design process is a detailed analysis of the needs of the users of the system that is to be designed. Regarding worker safety, it is difficult to ensure that any human intervention on an automated production system will be safely achieved if the designer has not properly identified and understood the context and constraints associated with this intervention. An automated production system has many different users: operators, maintenance people (mechanical, electrical), cleaning people, process engineers, etc. Needs identification and analysis enables the designer to clearly define the needs and constraints

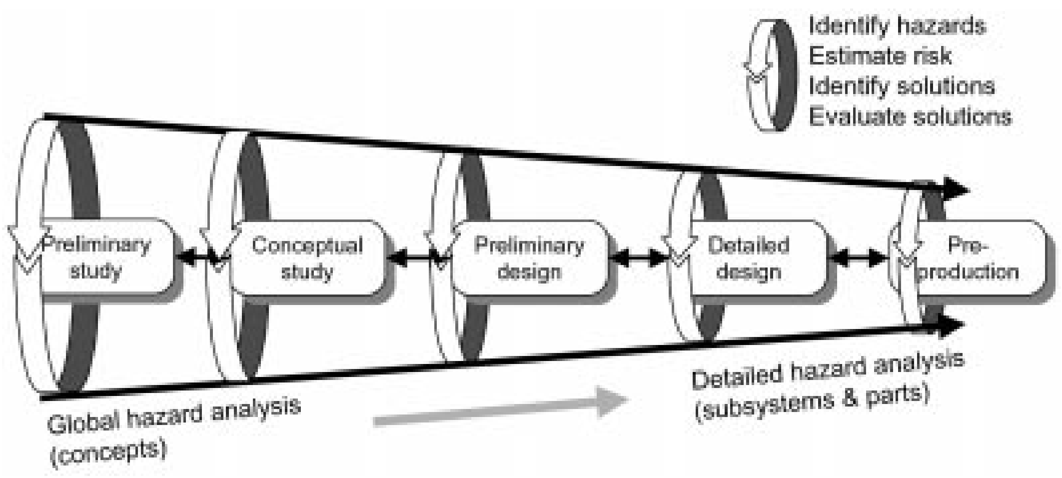

Fig. 2. Diagram of the integration of safety aspects into the design process.

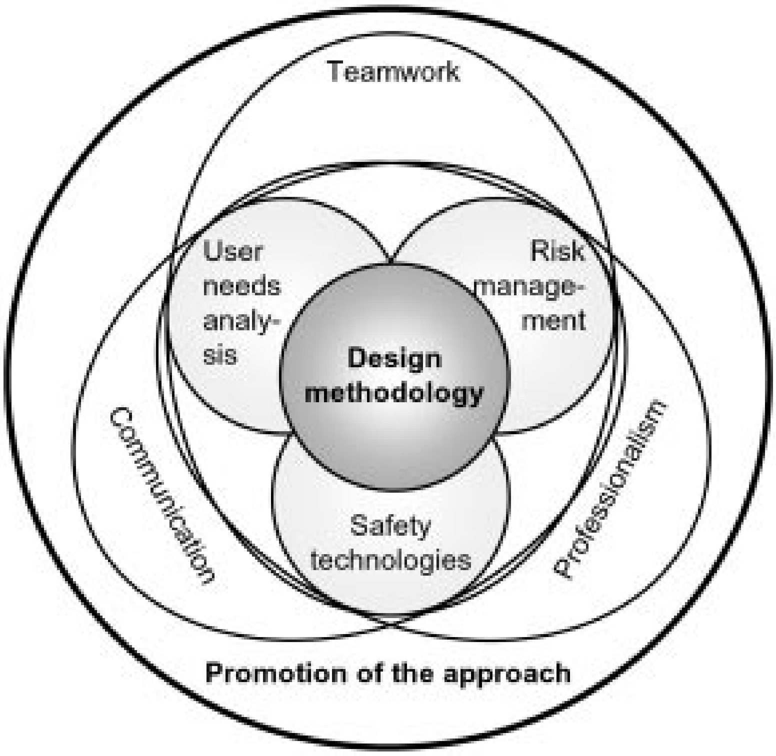

Fig. 3. The eight competencies to be developed.

of these users in relation to the system to be designed. Due to the growing complexity of automated production systems, a clear and simple expression of all of the needs relating to these systems is essential in meeting the safety objectives. It is therefore imperative that design engineers develop this competency and that they apply it in their work.

Competency in needs analysis consists of several sub-competencies that allow these imperatives to be better defined. Designers should first know how to recognize and collect information on the different types of needs (functionality, performance, comfort, safety requirements, etc.) of the various users or people working directly or indirectly with the automated system (operators, maintenance technicians, process engineers, etc.). To do this, they should also know and understand how to apply the different needs-analysis techniques and methodology, such as task analysis, functional analysis, focus groups, etc. Finally, they should be able to prioritize these different needs, using appropriate methods, in order to know how to optimize the necessary compromises when certain needs are technically or economically difficult to meet in full. Obviously, this competency should be applied throughout the design process in order to ensure a constant updating of the needs of all the people involved with the system.

This competency is also based on the need to consider the ergonomics of automated-system design. Without becoming experts in ergonomics, designers with this competency would be aware of the need to adapt the machine to man in order to achieve a higher level of safety, functionality and performance.

Safety technologies. Safety cannot be integrated into the design of complex automated systems without the contribution of so-called safety technologies. Design engineers must therefore know about these technologies and where, when and how to integrate them into the system. The purpose of having design engineers develop this competency is to make them aware of all the means available for control systems and devices and their hierarchy in order to control the risks associated with automated systems. This competency also focuses on providing them with the necessary tools to integrate and apply control and safety devices in such a way as to eliminate or reduce risks. In this respect, it fulfills a need explicitly formulated by the design engineers in the visited mills. This competency works directly with the competency in risk management, as it pertains to the selection of means or devices for controlling risks.

Risk management. Rigorous and systematic risk analysis methods are essential in the automated-facility design process, mainly because of the complexity of these systems and the many hazardous situations that they may generate. There are several risk analysis methods that can be used in industrial machine design [11]. The best-known methods include failure mode and effect analysis (FMEA), fault tree analysis (FTA), and hazard and operability study (HAZOP). However, many design engineers from all fields do not know about or have not mastered these risk analysis methods [17,18], and this study has shown that design engineers of automated systems in large processing industries are no exception.

To make up for this deficiency, competency in risk management focuses, among other things, on design engineers being able to choose the proper methods and apply them effectively in order to identify hazards and their causes at each step in the design process. Its purpose is also to enable them to evaluate risks, meaning to define the level of criticality that produces a certain hazard in relation to the probability of the hazardous event occurring and the seriousness of its consequences. Finally, this competency must ensure that design engineers know how to recognize the possibilities for controlling risks as close as possible to the source by acting on the identified causes.

Teamwork. Detailed needs analysis in automated system design generally reveals problems that can produce complex interrelationships. In most cases, it takes several disciplines to solve these occupational safety problems, requiring effective collaboration between many experts from these different fields [19, 20]. Concurrent engineering is now recognized by many authors as an approach that offers a possible link between design and safety by applying, right from the start of the design process, the knowledge of the various specialists in a global, systematic and multidisciplinary methodology [17, 21]. Safety must be integrated into the automated-system design process within a multidisciplinary framework promoted by exchanges and communication between the participants, as recommended in the philosophy of concurrent engineering.

Although a degree of teamwork exists in current design practice, certain basic principles and practices can be greatly improved, as shown by the findings presented above. Competency in teamwork therefore focuses on improving the ability of the people involved in automated-system design to work effectively in multidisciplinary teams. Direct collaboration between the different disciplines implicated in design (managers, project engineers, process engineers, instrumentation and control technicians and engineers, operations managers, etc.) is essential in identifying safety problems and then solving them efficiently. Among other things, the people involved should be able to appreciate the importance of multidisciplinary teamwork in automated system design, understand the dynamics of effective teamwork, and apply such dynamics throughout the project process.

Communication. This competency clearly falls into the same context as teamwork. In fact, the deficiencies observed in communication make it difficult to put competency in teamwork into practice. As a result, the lack of an effective communication process with potential users and with all the people involved in design has a negative impact on the integration of safety into automated systems. Competency in communication focuses on improving the capacity of the people involved in design to communicate effectively with people at different hierarchical levels and in different disciplines. It also focuses on their being able to clearly describe others' knowledge skills and experiences, first by identifying them and then by expressing them properly.

Ethics and professionalism. It is important to mention that, based on the research results, we can conclude that this competency has already been acquired by the majority of automated-facility design engineers. This essentially reflects an awareness of the critical role that designers of complex equipment can play in the safety of its users. In the framework of the training program, this competency is introduced as a reminder of the importance of recognizing situations in which ethics and professionalism come into play in the context of safety in automated facility design.

Promoting the approach. It is very unlikely that a training program such as the one considered here could rapidly reach all the people involved in automated-facility design in all mills. Therefore, the few people who will be trained and who will have developed the targeted competencies to a greater degree will have to, at least at the beginning, work in the same environment as the one in which they worked initially. These people will therefore have to demonstrate a certain leadership in order to influence their coworkers so that they also become aware of the need for taking safety aspects into account in all phases of the design process. It is here that the competency of promoting the overall approach comes into play, which focuses on transferring the necessary tools so that trained people can promote a safety-integration approach to their superiors, coworkers and subcontractors. As Fig. 3 shows, this latter competency encompasses all the other competencies. In fact, it is by knowing how to promote the design approach in which they were trained that they will be able effectively to apply the other competencies that they will have acquired.

DEVELOPMENT AND IMPLEMENTATION OF THE TRAINING PROGRAM

Training program characteristics

The eight competencies identified in the study were used as the basis for the development of an extensive training program whose purpose was to produce automated-system design engineers who are able to design for safety. The objectives of this training program were to provide opportunities for developing competencies that are recognized as being the basis for the desired expertise and to ensure that these competencies are transferable to different design situations. Thus, as previously mentioned, the choice of the research team was oriented towards a training program based on a transfer-of-competencies approach, since this approach allows a greater integration of the knowledge into the field of competencies. From the start of training, such a program places students in 'problem-solving', 'project execution' or 'case study' learning situations so that the developed knowledge is immediately finalized and operational in the competencies. Learning situations continuously prompt the students to consider their knowledge as a cognitive resource that can be mobilized into skills. Furthermore, learning situations focus a lot of attention on the transferability of competencies and knowledge and the students are regularly forced to consider several fields of transfer.

However, this approach involves a greater integration of knowledge and therefore requires that the training program be constructed in such a way that the links between the competencies, contents and pedagogical formulae and learning sequences be considerably more elaborate and defined. Consequently, the competencies could not be considered independently in the training program. They are, in fact, all interrelated and the complete acquisition of one competency is conditional on the acquisition of the other competencies, as illustrated in Fig. 3. Design engineers must therefore acquire these competencies through a logical process that allows this connection between competencies. This logical process is, in fact, the design process generally used by automated-system design engineers. Analysis done during the research led to the discovery of a common design process for automated systems in large-scale processing industries, which, without being explicit and formal, was observed in a great majority of the visited plants [22]. As an important result of this research, the research team made this process explicit and used it to interrelate each of the competencies in the design activities. These interrelationships include links with the input and output of these activities, as determined by their interdependencies. This representation also associates the resources (material and human) required for carrying out each activity in the design process in order to further contextualize the interrelationships. The result is a global and systematic design process, consisting of a total of almost 130 activities, which integrates safety into automated system design while being consistent with the needs of the design engineers. This process is the actualization of the integration of safety into the design process, as shown in Fig. 2.

The training program was therefore developed from the eight competencies by respecting the following structure: determining the sub-competencies, defining the learning objectives, describing the discipline-related content, determining the learning modalities and, finally, determining the training-support documents. The pedagogical aspects of the eight competencies were then connected in each of the steps of the design process, which became the backbone of the training program. All of the links between the activities in the design process and each of the outputs of each activity, the competencies, sub-competencies, learning objectives, discipline-related contents, pedagogical modalities, and training-support documents were entered in a detailed table. In this table, the pedagogical elements relating to the eight competencies were connected very specifically to the design activities, and all the links necessary for the specific preparation of the training as well as all the learning materials required, were coded.

Table 1 presents a brief overview of the descriptive table of the training program. In practice, this table has five major column categories:

1. The benchmarks relating to the design process; namely, the discipline involved, the specific activity, the type of output deliverable and its identification (alphanumeric coding).
2. The link to the competencies involved in each specific activity, including, among other things, the sub-competencies and the learning objectives (numeric coding).
3. The link to the discipline-related contents relating to each element in the two previous categories.
4. Pedagogical formulae (including, among other things, learning sequences, learning modalities, the expected duration of the sequence and its interrelationship with each of the previous or subsequent learning situations and its learning context).
5. The link to the required pedagogical material. This final category consists of a detailed alphanumeric coding for each required type of material in relation to the final user of this material and in relation to the pedagogical formula involved.

This table, in which all the links necessary for the specific preparation of the training as well as all the required pedagogical materials are coded, was the main tool used in constructing and managing the training.

Training program implementation and results

The first session of this training program, which lasts 24 days over 12 months, began in January 2000. Another session began in February 2001. The first two sessions were intended for engineers from all specialties involved in the design of automated systems in paper mills. Plant engineers as well as consulting engineers were invited to participate in this training activity.

In these initial training sessions, several interesting facts in the development of future training programs focused on the transfer of competencies could be observed. The learners' comments show that they are not used to such training. In fact, they

Table 1. Overview of the descriptive table in the training program.

Design activity			Sub-competencies		Learning objectives		Discipline-related contents		Pedagogical modality	Training support documents Reference #
#	Title	Output document	#	Title	#	Title	#	Title		
G.1.2a	Defining the problem and describing its consequences	Defining the problem and its consequences	2.0	Understanding and applying the problem-solving process	2.0.1	Understanding and applying the problem-solving process	2.0.1.b	Defining the problem and information collection	Role playing related to case study	DCT-F-1.106
G.1.3	Exploring the causes	List of possible causes of the problem	7.1	Being able to identify hazards and hazardous situations	7.1.2	Naming and comparing some methods for identifying hazards	7.1.2e	Fault tree analysis	Case study	DAPL-A-1.200
G.1.5	Defining the problem and describing its consequences	Defining the problem and its consequences	2.4	Developing valid and up-to-date documentation for the project	2.4.1	Recognizing the various documents that must be produced during design as well as their usefulness	2.4.1a	Properly documenting and discussing the observations made in the plants	Application case and discussion	DCT-F-1.110
G.2.1	Planning the project team	Project team and matrix of responsibilities	1.2	Understanding the dynamics of efficient teamwork	1.2.2	Positioning oneself personally (strengths and weaknesses) in relation to the dynamics of teamwork	1.2.2a	MBTI	Discussion and exercises	DSAP-AF-1.502
G.2.3	Identifying the typical hazards (retrospective analysis)	Preliminary list of hazards	2.1	Applying efficient and safe design approaches, methods or guides	2.1.2	Recognizing and explaining the key elements in an efficient and safe design methodology	2.1.2c	Strategic integration of safety	Lectures	DAPL-F-1.101
G.2.3	Identifying the typical hazards (retrospective analysis)	Preliminary list of hazards	2.2	Applying standards and regulations	2.2.1	Standards	2.2.1a	Standards organizations, their standards and government regulations	Discussion	DCT-A-1.351
G.2.3	Identifying the typical hazards (retrospective analysis)	Preliminary list of hazards	7.1	Being able to identify hazards and hazardous situations	7.1.1	Recognizing and identifying typical hazards of machines in the paper industry	7.1.1a	Introduction, definitions and general information on the identification of hazards	Discussion and examples	DSAP-AF-1.503

expect to receive knowledge in an already constructed form in terms of problems involving finished solutions that can be directly generalized or applicable to their situation. These expectations, which are consistent with more traditional approaches, allow much more information or knowledge to be given in a relatively short time. However, knowledge thus transmitted is not well integrated by learners who are not confronted or forced to question themselves. Such learners tend to retain only what they considers important and consistent with their interpretation framework of the reality of the problem and solution. The result is a small transfer of competencies, and, consequently, little change in work methods in the reality of the professional environment. Training by competencies, such as the one developed in this research project, has clearly affected this usual order by promoting the introduction of new knowledge in a complex problem-solving process in which the learner is paradoxically confronted with the desire to learn and the recognition of a certain incompetence. What seems to emerge from current experience is that the trainers, who have very complex expertise and competencies that must be transferred within the scope of such a training program, do not necessarily have all the required relational and pedagogical competencies for such training.

These difficulties are exacerbated by the fact that, when learners integrate new knowledge in detail, they can lose sight of the learning they have achieved. Since the new knowledge is integrated into the competencies, learners do not have an overview of the path taken and so are not directly able to see the extent of the change. They therefore do not have an impression of having learned as much as in a traditional program in which the amount of knowledge is more obvious, even though the extent of the actual change may be modest.

These particular difficulties were more obvious with the first group. Trainers faced with these difficulties had to question themselves and improve this aspect of the training. Learners construct a knowledge diagram that describes links with the newly acquired knowledge after each session or three-day training session, so that they can trace the path of their learning and recognize the extent of the changes that have taken place.

Initial observations of the implementation of this type of training program show the pertinence of the competencies to be transferred and the potential for change in the designer's practices. It seems that particular attention must be paid to the specific support required by trainers involved in this type of program.

DISCUSSION

Although this research project was conducted in the pulp and paper industry, the results are relevant to other types of industries with the same automated-equipment safety problems. Aluminium plants and sawmills, to name only a few, are plants in which production automation is important. However, the researchers have chosen not to offer the training program to engineers in environments other than paper mills without a prior study. Two reasons justify this decision. First, the entire training approach is based on a detailed design process specific to paper mills which is the result of a thorough analysis of such plants. Other large-scale processing industries undoubtedly have variations in their design process that need to be addressed. Second, there is a need to consider the interrelational aspects that determine the design engineers' work, as well as to ensure their genuine motivation and the openness of the milieu before attempting to implement a change process. Several safety studies, which are normally confined to the limited context of technical aspects, have identified only a narrow layer of the complex problems linking occupational health and safety to the dynamics of the design process. Without a more general systematic approach, the interrelational aspects that determine the technological solutions and appropriate choices cannot be considered. These aspects have an existence and specificity that cannot be determined outside the actual workplace involved. This is why, from the start, this research project was deliberately oriented towards a methodology based on a field approach. Furthermore, significant changes in the designers' professional behavior cannot occur without sincere motivation on their part. The openness of the milieu—the people concerned, as well as the plant, meaning the institution—would have been impossible without a relationship of confidence promoted by the many visits, mutual respect, and the credibility of the research team. In this project, the objective was not to impose one or more solutions (whose content generally is almost exclusively technical), but instead to develop the designers' autonomy. This autonomy cannot evolve without their active participation in finding solutions, hence the decision to develop a training program based on the transfer of competencies. The chosen approach and methodology took these necessities into account from the start.

As a result, any process to transpose the results of this research to other fields should be preceded by a field analysis and validation. The methodological approach of the study, as well as the proposed solution approach (a training program based on competencies) and general competencies, are generic, but their application to different contexts must be adapted and validated within the specific field.

CONCLUSION

The promotion of the development of these eight competencies through training should, for the most part, correct the problems and meet the needs identified during the study and presented in this paper. This should enable industrial system-design engineers to adopt better practices and develop safer and more global solutions that are better integrated into and better adapted to the situations and reality of the industrial world. In this respect, the firsts cohorts of trained professionals will be evaluated as follow-up to this research project. The results of the training program will be evaluated from the viewpoint of the trained people and also of other relevant people in their surroundings: superiors, coworkers, production and maintenance workers, etc. The impact over the medium term on the general safety of automated facilities will also be evaluated from a longer term perspective. These evaluations will validate this type of preventive approach as well as the chosen competency-transfer process, and allow the training parameters to be adjusted as needed.

Acknowledgements—This research project was made possible due to the financial support of the Institut de Recherche en Santé et en Sécurité du Travail du Québec. The authors wish to thank all the participants from the Quebec pulp and paper industry for their invaluable contribution, as well as all the other people who contributed to this project. Finally, the authors want to acknowledge the help of all members of the research team in the preparation of this article: Gilles Bouchard, Réal Bourbonnière, François Charron, Cécile Collinge, Patrick Doucet, Marc Mileshik, Caroline Monette, Joseph-Jean Paques, Domenica Schiralli, Jacques Tardif and Mario Touchette.

REFERENCES

1. J. Graham, W. Karwowski, H. Parsaei, and J. Zurada, Concurrent Engineering for Enhancing Worker Safety in Robotic Workcells, in P. T. Kidd and W. Karwowski (ed.), *Advances in Agile Manufacturing: Integrating Technology, Organization and People*, IOS Press, Amsterdam (1994) pp. 79–82.
2. M. Mattila, T. Tallberg, V. Vannas, and J. Kivisto-Rahnasto, Fatalities at advanced machines and dangerous incidents at FMS implementations, *International Journal of Human Factors in Manufacturing* (1995) pp. 237–250.
3. V. Vannas and M. Mattila, Safety aspects in FMS implementations, *International Journal of Human Factors in Manufacturing*, **6**(2) (1996) pp. 163–179.
4. T. Backström and M. Döös, The technical genesis of machine failures leading to occupational accidents, *International Journal of Industrial Ergonomics*, **19**(5) (1997) pp. 361–376.
5. V. L. G. Blank, L. Laflamme, and R. Andersson, The impact of advances in production technology on industrial injuries: A review of the literature, *Safety Science*, 26(3) (1997) pp. 219–234.
6. R. Edwards, P. Nicolaisen, and J.-P. Vautrin, *Robots et ensemble automatisés*, INRS (France), Cahier de notes documentaires No. 149 (1992) pp. 455–478.
7. P. Doucet, *Développement d'une méthodologie de conception permettant l'intégration sécuritaire des automates programmables industriels (API) et des systèmes de contrôle distribués (SCD) aux systèmes de production automatisés destinés à l'industrie québécoise des pâtes et papiers*, Masters thesis, Université de Sherbrooke (1998).
8. J.-J. Paques, *Règles sommaires de sécurité, pour l'utilisation des automates programmables industriels (API), Étude/Bilan de connaissances*, Institut de recherche en santé et en sécurité du travail du Québec, Montreal, 19 p. (1991).
9. J. Tardif, Le transfert des compétences analysé à travers la formation de professionnels, *Colloque international sur les transferts de connaissances en formation initiale et continue*, Lyon (1994).
10. J. Tardif, R. Benoît, F. Gauthier, Privilégier une approche par compétences dans la formation continue des ingénieurs responsables de la conception de systèmes automatisés pour les papetières, *International Conference on Safety of Industrial Automated Systems*, IRSST, Montreal, October 1999.
11. F. Gauthier, *Développement d'une approche méthodologique permettant l'intégration systématique des aspects de la santé et de la sécurité du travail dans le processus de conception d'outils, de machines et de procédés industriels*, Doctoral thesis, Université de Sherbrooke, 270 p. (1997).
12. C. Collinge and F. Gauthier, Conception des systèmes automatisés dans les papetières québécoises: apport de l'ergonomie dans le travail des ingénieurs-concepteurs, *International Conference on Safety of Industrial Automated Systems*, IRSST, Montreal, October (1999).
13. J. A. Stoop, *Safety and the Design Process*, Doctoral thesis, Delft Technology University, Netherlands (1990).
14. T. A. Hunter, *Engineering Design for Safety*, McGraw-Hill (1992).
15. M. Reunanen, *Systematic Safety Consideration in Product Design*, Doctoral thesis, Technical Research Center of Finland (1993).
16. M. Reunanen, Systematic safety analysis methods in product fesign, *International Conference on Engineering Design*, The Hague, Netherlands (1993) pp. 1174-1181.
17. B. W. Main and A. C. Ward, What do design engineers really know about safety?, *Mechanical Engineering*, **114**(8) (1992) pp. 44–51.
18. B. W. Main and J. P. Frantz, How design engineers address safety: What the safety community should know, *Professional Safety*, 29(2) (1994) pp. 33–40.
19. R. L. Brauer, *Safety and Health for Engineers*, Van Nostrand Reinhold, New York (1994).
20. F. Gauthier and F. Charron, Design for health and safety: A simultaneous engineering approach, *International Conference on Engineering Design*, Czech Technical University, Praha, Czech Republic (1995) pp. 891–896.
21. D. G. Raheja *Assurance Technologies, Principles and Practices*, McGraw-Hill (1991).

22. R. Benoît, F. Gauthier, and P. Doucet, Intégration méthodologique des aspects de sécurité du travail au processus de conception des systèmes automatisés utilisés dans les papetières québécoises, *International Conference on Safety of Industrial Automated Systems*, IRSST, Montreal, October (1999).

François Gauthier has been a professor of industrial ergonomics and safety in the Industrial Engineering Department of the Université du Quebec à Trois-Rivières since 1998. He received his M.Sc. (1994) and Ph.D. (1997) from the Université de Sherbrooke (Canada) in the field of engineering design for safety. His current research interests are in the development and application of safety analysis methodologies in the concurrent engineering design process.

René Benoît has been a researcher in occupational health and safety in the Engineering Department of the Institut Robert-Sauvé en Santé et en Sécurité du Travail du Québec since 1992. He received his M.Sc. in 1987 from the Université de Sherbrooke (Canada) in the field of mechanical engineering and he does research in many different areas of occupational health and safety (OHS). His current research interest is in combining analytical and systemic approaches in order to develop an integral systemic action-research methodology. One objective is to apply this new methodology to the development of new and more effective ongoing-training programs focusing on a real change in engineering practice.