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Human factor risk management in the process industry: A case study

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ABSTRACT

In this work, a new procedure called Human Factor Risk Management (HFRM) was developed in order to integrate Human Factor in a Refinery Risk Management System. Taking into consideration historical data regarding Environmental Accidents, Near miss, Injuries and Operating accidents occurred in a refinery over the last years a panel of experts defined the performance shaping factors (PSFs) and risk associated with adverse events. A conceptual model, based on Association Rules (AR), has been proposed for investigating the network of influences among adverse event typology, human error causes, refinery plant area involved in the adverse event, performance shaping factors (PSFs), risk index and corrective actions.

The results obtained using the association rules method proved to be useful for assessing human practices and human factors which influence high-risk situations. The human factor analysis carried out in this paper was planned as a dynamic process and can be repeated systematically. The association rules technique, taking into consideration a wide set of objective and predictive variables, shows new cause–effect correlations in refinery processes never described previously, highlighting possible adverse events and supporting decision-making in these areas.

1. Introduction

The analysis of human factors and their connection with safety management has been pointed out after the Three Mile Island Accident. The analysis of this case brought great changes in dealing with human performance problems especially in the companies involved in hazardous activities [1]. A better understanding of human error and its consequences can be achieved through the application of human factor identification models. To accomplish this, the human error must first be removed from the emotive area of blame and punishment and engaged in a systems perspective. From this point of view, the human factor is treated as a natural consequence arising from a discontinuity between human capabilities and system demands. The factors that influence human error can then be documented and managed. Such efforts are an essential component in an overall scheme of process safety management [2]. According to Cacciabue [3], the need to include Human Factors considerations in the design and safety assessment processes of production systems is generally accepted by almost all stakeholders. The process of safety management consists of well-defined steps aimed at avoiding losses and identifying opportunities to improve security, quality and, as a consequence, performance in an organization [4]. The attitude that is generally adopted towards industrial activities is a cost-benefit approach: The activity is undertaken if it provides economic benefits that justify and reward the effort of undertaking it. Risk management is part of these efforts and has to be carried out in order to avoid losses that will overwhelm every reached, promised or foreseeable benefit.

Current accident experience suggests that so-called high-risk industries are still not particularly well protected from human error. This, in turn, suggests the need both for the means of properly assessing risk attributable to human error and for ways of reducing system vulnerability to human error impact [5].

In this paper we propose a Human Factor Risk Management (HFRM) methodology that, using the synergies provided by the simultaneous adoption of risk and human factor analysis, enables continuous improvement process in terms of plant reliability at the lowest possible cost. Human Factor Risk Management procedure was developed in order to integrate Human Factor in a Refinery Risk Management System.

The drivers for developing a new Human Factor Risk Management (HFRM) model are:

1. Integration of human factor risk management into the organization as a part of achieving their overall goal of a managed corporate culture.
2. Increase the human factor contribution to company functions and activities.
3. Provide, for every refinery plant, risk reduction recommendations to mitigate the potential for human error.
4. Reduce costs arising from human performance limitations and add value through improved human performance.
5. Meet demand for business owners and high-level managers.

In a processing industry like a refinery, the number of annual failures is likely to be very high, partly as a result of the normal wear of the components which are often subject to intensive working conditions [6]. Within this context, this study attempts to identify the human practices and factors which influence high accident risk situations. The Safety, Quality and Environment (SQE) committee of the refinery has shown that human error is a main contributory cause to more than 30%

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Table 1
Human causes list.

Human error causes (practices or actions below standards)
Operation carried out without authorization
Necessary operation/procedure was forgotten
Incorrect choice of raw material
Lack of precision/inappropriate speed of performance/haste
Warning given incorrectly/insufficiently/to the wrong person
PPE (Personal Protective Equipment) used badly/faulty
Inadequate knowledge of regulations and procedures
Made inoperative a control system
Incorrect loading/lifting/substitution of equipment
Incorrect/inappropriate use of equipment/appliances
Incorrect position or posture during the developed activity
Maintenance/action/operation carried out on equipment in run
Bad habits
Lapse of concentration/detrimental behavior

of adverse events, 70% of which could have been prevented by management actions. The SQE committee identifies as human errors what Reason [7] called “Person Approach”, the longstanding and widespread tradition of the person approach focuses on the unsafe acts—errors and procedural violations. The percentage of adverse events connected to human errors is evaluated using historical data collected by the refinery and based on a human causes list (see Table 1). Human errors committed during the design and construction phases of the refinery plants are not included. If more than 30% of the causes of adverse events are related to “human error”, that means that different aspects and different items are grouped under this voice. The use of a sound classification can be useful to better specify and direct the study towards methods of prevention [8]. Unfortunately, in the field we are approaching there is no universally agreed classification system, hence the taxonomy we would like to adopt must be made for our specific purpose.

The principal result of any classification process is that interpretation can improve problem-solving performance in the area of interest [9]. Therefore, classifying and finding relationships among a set of variables is a complex and common problem even in Risk Management.

In the present work, with specific reference to a medium-sized refinery, all the information useful for identifying the factors which lead to critical events in the workplace was collected. A thorough understanding of the variables which influence a particular problem is essential for finding increasingly efficient solutions. Nevertheless, a great deal of data is often collected which is difficult to understand, considering the number of variables involved. As a Data Mining technique, Association Rules methodology is promising because of its advantages over standard statistical techniques. The use of statistical techniques, such as linear regression, is based on general assumptions regarding the data set, which are normally difficult to satisfy. In the case examined here, the intrinsic structure and complexity of the data collected might jeopardize the use of traditional tools for analysis since the variables presented some critical aspects. First of all the high number of predictive variables is a problem of considerable importance for standard statistical analysis in general. Moreover, a parametric analysis typically adopts the independence hypothesis while the relationships between the independent variables can be a problem in this study. Finally, we have to face the non-homogeneity and non-linearity distribution of data collected.

From this point of view, Association Rules are a valid alternative and complementary tool to parametric methods, guiding the researcher towards a more thorough understanding of the data.

When employing Logistic Regression (LR), it may be difficult to understand the impact of an individual risk factor or interplay between multiple risk factors. Researchers typically need to formulate a hypothesis for each risk factor combination before doing a formal evaluation, which may become practically infeasible even for a moderately sized set of variables. On the other hand, in Data Mining, many patterns may be extracted in a single run, but many resulting formats are of low readability. Association Rules may be used to avoid these problems because it provides: 1) numerous readable patterns (rules) that describe the interaction between variables; 2) more straightforward interpretation than for the LR coefficients; and 3) numerous interpretable measures of rule interest, which facilitate identification of relevant rules and rule comprehension.

The rest of the paper is organized as follows. Section 2 presents the literature review about methods and procedures for analyzing the human factor and human error in the industry. Section 3 describes the research approach proposed in this work analyzing in the sub-sections all phases of the Human Factor Risk Management (HFRM) procedure. In Section 4 a Human Factor Risk Analysis methodology application is used to illustrate the application of the proposed method. In Section 4.1 the results obtained are discussed. Finally, the conclusions are presented in Section 5.

2. Literature review

The first classification and description of human reliability assessment methods has been developed by Bell and Holroyd [10]. They identified 72 potential human reliability related tools and 17 of these tools were considered to be of use to Health and Safety Executive (HSE) major hazard directorates. They highlighted that different tools may be appropriate depending on the ‘maturity’ of the site with regard to quantified human risk assessment. Another interesting classification of Human Factor and Human Assessment Reliability methods has been proposed by Calixto et al. [11]. They suggested a classification according to three stages in time. The first twenty years (1970–1990) is known as First Human Reliability Methods Generation, which focuses on human error probabilities and operational human error. The Second phase, the next fifteen years (1990–2005) is known as second Human Reliability Methods Generation and focuses on Human performance Factor and cognitive processes. Finally, the third phase started in 2005, continues today and is represented for methods that focus on human performance factors relations and dependencies.

The majority of work in human factor and human error prediction in industry has come from the nuclear power industry through the development of expert judgment techniques such as Success Likelihood Index Methodology (SLIM), Human Error Assessment and Reduction Technique (HEART) and Technique for Human Error Rate Prediction (THERP) [12]. The lack of human error data and the potentially severe consequences of nuclear industry accidents led to an extensive use of methods based on expert judgment.

The success likelihood index methodology (SLIM) was developed under the sponsorship of Brookhaven National Laboratory and the U.S. Nuclear Regulatory Commission to quantify operator actions in the plant response model of a probabilistic risk assessment. This technique is based on the assumption that the human error rate in a specific situation depends on the mutual effects of a relatively small set of performance-shaping factors (PSFs) that impact on the operators’ ability to perform the action successfully. Since the comparative work by Kirwan et al. [13], SLIM has evolved into a widely known expert judgment technique that employs judges to provide numerical feedback that is used as input to formulate the probabilities connected to the human error. The SLIM technique has taken on several forms since its initial development and follow-on modification. An example is the Failure Likelihood Index Method (FLIM), which utilizes a Failure Likelihood Index (FLI) as opposed to a Success Likelihood Index (SLI) (Chien et al., [14]).

Dougherty and Fragola [15] analysed time reliability correlations (TRCs) to predict the probability of failure of an action. A TRC is a probability distribution based on the time to complete an action and the actions likelihood of success (Di Mattia et al., [16]). The Dougherty and Fragola approach was based on the idea that if an accurate diagnosis is not developed within a critical period of time, then a failure occurs. Kirwan [13] carried out an in-depth review and evaluation of a wide range of Human Error Identification (HEI) techniques. SLIM was treated as a means of calculating HEPs but was not assessed together with other techniques such as THERP. Kirwan noted that communication in emergency and routine situations is often a contributor to, or a cause of real events. Kirwan's work also strengthens the importance and role of human error in risk assessment and stresses the need to adopt a scientific approach toward predicting and managing human error. Zamanali et al. [17] applied SLIM through a team that included operators, to predict Human Error Rates (HERs) for a processing plant. PSFs were treated as directly acting and indirectly acting. Weighting factors were calculated by expert judgment via a pairwise comparison of the importance of each PSF relative to the other. Spurgin and Lydell [18] reviewed both SLIM and FLIM along with HEART and THERP. An important comment by Spurgin and Lydell is that there still exists a significant gap between academic research and practical HRAs. Khan et al. [19] developed a Human Error Probability Index (HEPI) based on the SLIM approach. This approach tries to limit the opportunities for human error occurrence and mitigates the results of such errors through changes in training, design, safety systems and procedures.

Some disadvantages of the above procedures have been highlighted by Richei et al. [20]:

- Lack in quality of reliability data and questionable transferability;
- Insufficient criteria for choosing PSFs.

Other approaches tried to include cognitive and dynamic considerations in Human Reliability methods. Cacciabue [21] proposed a methodology called Human Error Risk Management for Engineering Systems that offers a 'roadmap' for selecting and consistently applying Human Factors approaches in different areas of application and also contains a 'body' of possible methods and techniques of its own. More recently Bevilacqua et al. [22] proposed a new approach based on fuzzy cognitive maps for analysing relationships among human factor, organisational factors, working conditions and injury events.

Some authors presented a methodology based on Bayesian Belief Networks (BBN) for analyzing human reliability and they applied this method to industrial contexts. Martins and Maturana [23] applied this method to the operation of an oil tanker, focusing on the risk of collision accidents. This method tries to overcome the THERP problems regarding the possibility to model the representation of individuals, their interrelationships, and the dynamics of a system. Also Calixto et al. [11] tried to use the Bayesian Network methodologies for analyzing human factors. In particular, the authors compared SLIM, SPAR-H and Bayesian Network methodologies. They found similar results, but the Bayesian Network method is harder to be applied and to obtain the reliable answer from specialists due to the complexity of such a method, while the simplest method to be applied is the SPAR-H. In order to overcome this problem, Groth and Swiler [24] developed a BBN version of the widely used SPAR-H method. They demonstrated how this approach can be used by HRA practitioners also incorporating data and new information.

Recently, Deacon et al. [25] proposed a research method which included the Human Error Assessment and Reduction Technique (HEART) to estimate the likelihood of occurrence, and the use of historical data to estimate consequence severity. In this work, a combination of expert judgment techniques and major accident investigations from industry were used to evaluate the risk for the evacuation stage. An interesting method has been proposed by Aras et al. [26]. In this work, the authors presented a novel risk assessment model considering human factor based on the fuzzy logic approach. Abbassi et al. [27] integrated the SLIM Method with the THERP framework to generate the nominal HEP data when it is unavailable.

The majority of the studies proposed in literature only marginally developed a procedure for integrating human factor analysis with Safety, Quality and Environment (SQE) management system. The Human Factor Risk Management (HFRM) model developed in the current work is an attempt to help bridge this gap and provide meaningful human error reduction suggestions developing a procedure based on Association Rules. The Association rule learning technique has never been applied in this research field and it allowed us to uncover hidden patterns and unknown correlations among large and varied datasets related to human error, human factor, risk assessment, plant/working operative conditions and corrective actions.

3. Research approach

The Refinery is equipped with an integrated Safety, Quality and Environment (SQE) management system. The procedure used to analyse and report the adverse event is structured as a part of the SQE management system (Fig. 1). The starting point of this procedure can be connected to: 1) a work order, related to a corrective, on condition or planned maintenance (analysed by the Reliability Department of the refinery), 2) an accident, an injury, a near miss and a non-conformance (analysed by the Safety & Quality Department).

The term "work orders' ' refers to a set of activities such as orders to purchase new components, replacement of components, failure analysis, plant servicing, etc. The responsibilities identified for the correct functioning of the procedure involve both the workers and the refinery Departments. As far as the workers are concerned, each head of a shift, when issuing a work order (WO), must fill in properly all the items required by the Computerised Maintenance Management System (CMMS) present in the refinery. CMMS also collects the design and feature of all items (plants, equipments, etc.) to manage. In order to analyse the most relevant "work orders" only those tasks satisfying at least one of the following conditions are taken into consideration (see Appendix 1 for the definitions): Associated with a Critical Item, Associated with a Bad item, Maintenance costs of over €10,000, Cause of plant shutdown or slowdown or Issued in an emergency or urgent situation.

Any accident, injury or "near miss" no matter how slight the injury or damage, must be reported immediately to the supervisor of the area where it occurred for appropriate action. The supervisor is responsible for taking appropriate follow-up action, including getting medical attention for the injured and completing an investigation report in order to provide the event description. The Italian law requires that certain work-related accidents are reported to the local authority and to the SQE committee.

The identification of a non-conformance is the responsibility of all the personnel in the refinery, contractors included. The non-conformance has to be reported to the supervisor of the area where it occurred. The supervisor then collects the information in order to develop an event description and order the first actions needed for bringing the situation back to a safe condition.

Hence, the adverse event analysis is divided into different procedures from the analysts of the refinery according to the event cause. In particular, the Reliability Department analysts and Safety & Quality Department analysts, analysing the description of adverse events developed by heads of shift and refinery area supervisors, decide if events are related to human error. If the event description is not clear the analysts carry out face-to-face interviews with the refinery operators involved in the adverse event.

If the adverse event is not related to human error, the analysis follows the traditional procedure, otherwise, the analysis is carried out according to the HFRM procedure (Fig. 1). For the human factor, it has been proposed to modify the analysis format according to a different SQE management strategy. The HFRM procedure is based on risk assessment, a method of analysis for risks connected to human errors. The method is based on the association rules and proceduralized judgment of a group of experts in relation to the event under scrutiny.

3.1. Human factor risk management (HFRM) procedure

The development of HFRM procedures and the integration with the refinery SQE management system was carried out by a panel of experts called the Human Factor Risk Group. A panel of experts was formed in order to encourage communication and meetings where the operators

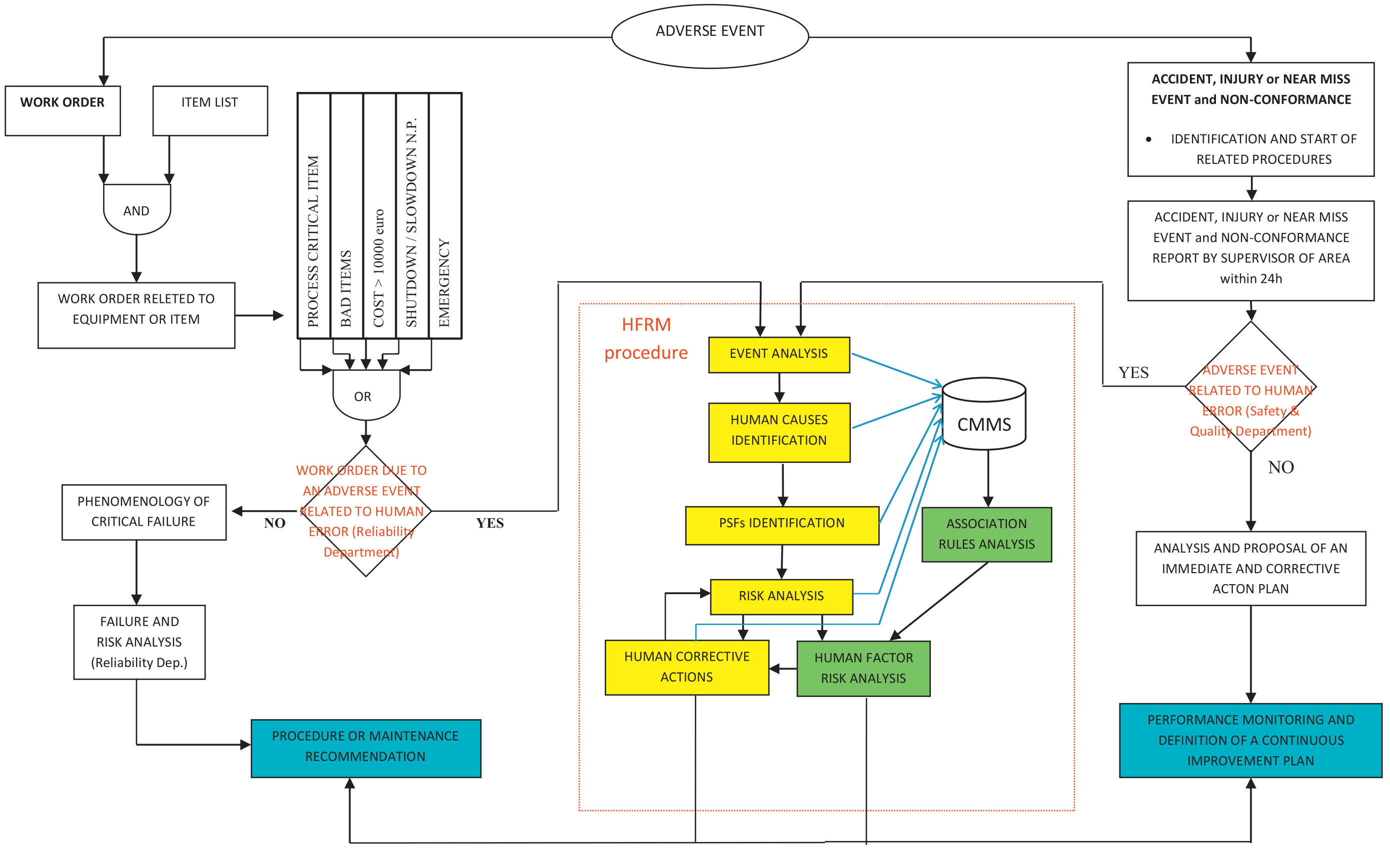


Fig. 1. Adverse event analysis and HFRM procedures.

could contribute their knowledge and information about the processes. The panel was made up of 12 participants, including 2 academics, whose research studies were mainly focused on risk analysis and data mining, 3 technical operators and 4 managers involved in the SQE committee and 3 operators involved in the Reliability Department and in the Safety & Quality Department.

The procedure developed by the Human Factor Risk group, as a part of the refinery SQE management system, is structured in the following steps:

(1) Identification of all the relevant information about the adverse events and event description.
(2) Identification of the human error causes.
(3) Examination of the events, evaluating the Performance Shaping Factors weights.
(4) Evaluation of the events in terms of real or potential risk.
(5) Identification of the follow-up actions in order to prevent or mitigate the event consequences.

The identification and the event description is the responsibility of the heads of shift or refinery area supervisors, as previously described. Points 2 to 5 are carried out by analysts of the refinery: the Reliability Department analysts take charge of the analysis of adverse events connected to work orders, while Safety & Quality Department analysts take charge of all other adverse events typologies.

Moreover, the procedure consists of a human factor assessment activity (green text boxes in Fig. 1). This is a monthly activity carried out by the Human Factor Risk Group. The Group, using the data collected in the CMMS and results obtained by association rules analysis, identifies the root causes of human errors and analyses the relationships between all variables connected to the adverse event (i.e. plant typology, equipment parameters, human error causes, PSF weights, Risk assessment, …).

All the HFRM activities are explained in detail in the following sections.

3.1.1. *Event analysis*

The refinery has a Computerised Maintenance Management System (CMMS) where various data for each adverse event that occurs must be registered: type of adverse event, the work situation or the way in which the event occurred, date of the event, the plant area where the event occurred, the part of the body injured and the description of the event. According to the refinery historical data, the adverse events have been distinguished in:

- “Near miss” -potential damages to health, processes and environmental, small chemical and gas loss, temporary gas and liquid plants out of use;
- “Accident or Injury” - injury, explosion, fire, collapse, damages to company and stakeholders property, serious chemical and gas loss;
- “Operating accident” - production loss, delays in plant set-up and products delivery, products out of specification, increase of consumption, plants stop;
- “Environmental accident” - scattered and funnel atmospheric emissions, waste and water discharges, abnormal noises and bad odors, external claims, emission or smoke peaks, abnormal fumes from the refinery torch.

Plant areas where the event occurred have been classified according to the processing at the refinery; topping, catalytic, reforming, isomerization, vacuum, visbreaking, thermal cracking cycle.

An integrated gasification combined cycle power plant is actually operated in the refinery. This plant burns a synthesis gas obtained from heavy oil refining products gasification plant. This plant has auxiliary oxygen production, gas washing, sulphur recovery, effluent treatment and heavy metals recovery utilities.

3.1.2. Human causes identification

The terms ‘human factors’ and ‘human error’ are often used interchangeably, but, as pointed out by Gordon [28], it is important to distinguish between the underlying causes of accidents (human factors) and their immediate causes (human errors). In this work, the Human Causes Identification step is carried out in order to define human error, while the human factor is analysed in the next step, PSFs identification and weight.

The adverse event reporting system in the refinery is structured in such a way that for each event the analyst of the “Safety Department” should report human error causes.

The questions to be faced in order to define the error causes are: Why did it happen? What human practices or actions led to the event?

In HFRM procedure the human causes to be selected must be chosen from a defined list (Table 1). This list has been developed in accordance with an internal procedure applied by the Shell Company (S-RCM, [29]) which was specifically created for the refinery sector.

If the cause is not listed in Table 1 the analyst reports “other”, providing an event description.

3.1.3. PSFs identification

“Human errors,” are the mistakes people make often resulting from human factors (Elise and Sierra, [30]). Performance Shaping Factors (PSFs) are those factors, or aspects, characterising the environment in which the event has occurred and the particular operative context (e.g.: the human-machine interface in a control room, the level of training required for the task in a complex system, and so on). In general, Performance shaping factors (PSFs) are those parameters influencing the ability of a human being to complete a given task. The probability of an error (incorrect action) is dependent on the relevant performance shaping factors (PSFs) (Khan et al., [19]). The application of PSFs in human reliability analysis of emergency tasks is seen as an important factor in human reliability assessment (Kim and Jung, [31]).

An initial list of PSFs has been defined carrying out a systematic literature review. A systematic literature search was conducted in relevant literature databases including Emerald, Metapress, Science Direct, Scopus, and Web of Science, using keywords such as “Performance Shaping Factor”, “Human Factor”, “Human Performance Factor”, “Human Reliability Assessment” and “Human Error Probability” .

Subsequently, different filters helped to identify and select substantively relevant studies constituting the core set of articles for data synthesis and analysis. The filters were defined as follows:

- Filter 1. Ensure substantive relevance, defined as adequacy of the articles in addressing and capturing the phenomenon under investigation (Brinberg and McGrath, [32]), by requiring that they contain the keyword search in their title, abstract or keywords;
- Filter 2. Consider only English language articles.
- Filter 3. Remaining abstracts should be read for substantive relevance.
- Filter 4. Remaining full articles should be read for substantive relevance.

No time limit or limit in publication type was adopted in these searches. Through the application of the first two filters to the keyword search phase, 32 papers were identified, of which 14 were defined as relevant (Filter 3 and 4) for this literature review study. The analysis of these articles allowed Human Factor Risk Group to define the 35 PSFs (see Appendix 2, Table 10). A set of seven PSFs was targeted to analyse the human factor at the refinery from becoming too unwieldy. To determine the relevance and the pertinence to the refinery context, each PSF was judged against the remaining PSFs in the set.

A PSF rank (λ) was determined by the equation:

$$\lambda = \sum occurences\ of\ PSF_i \quad (1)$$

This pairwise comparison is a simple qualitative method of determining the relative importance of each PSF. The top eight PSFs were used in the HFRM procedure. Table 2 shows the most relevant PSFs.

Table 2
PSFs.

Performance Shaping Factors (PSFs)
Training level
Available time for task execution
Attention towards suppliers/stakeholders
Human-machine interface
Quality of Information (lack of communication)
Company safety culture
Level of Experience
Lack of Supervision

PSFs are used within the HFRM procedure to identify contributors to human performance and to provide a basis for quantifying those contributors systematically. While completing an HFRM, the refinery analyst reviews the list of possible PSFs in order to identify possible sources of human error.

3.1.4. Risk analysis

A **Risk Index is** also calculated for each adverse event connected to human error. The selection of risk analysis methods and their results, in terms of frequency of occurrence and severity of consequences, is the focal point of the whole SQE management system and its procedures. In the European Union, the Seveso III Directive requires companies that store certain amounts of dangerous liquids or gases to introduce appropriate measures to reduce the potential risks.

In this work a risk index for each case of adverse event was calculated as the product of 2 factors: Probability × Consequence;

Probability: The likelihood of the considered accident occurring. In the case of the refinery, the Human Factor Risk Group defined some criteria, which are illustrated in Table 3. The probability that an event will occur is quantified assigning a class, from 1 to 5, to the possible scenario.

Consequence: The outcome of the adverse event. Failure of equipment in a refinery can be extremely dangerous for health and/or safety due to toxic products, high pressures and high temperatures during the processes. The severity of the accident can be decided with reference to Table 3. Four categories of possible consequences have been considered by the expert: effects in terms of potential injuries (Health and Safety), environmental impact, loss of reputation and economic loss. A level of severity, from 1 to 5, was then assigned to each impact category. The economic impact of an adverse event can be related to the damage to the property (costs for the repair and substitution of the equipment) or with the costs associated with the loss of production.

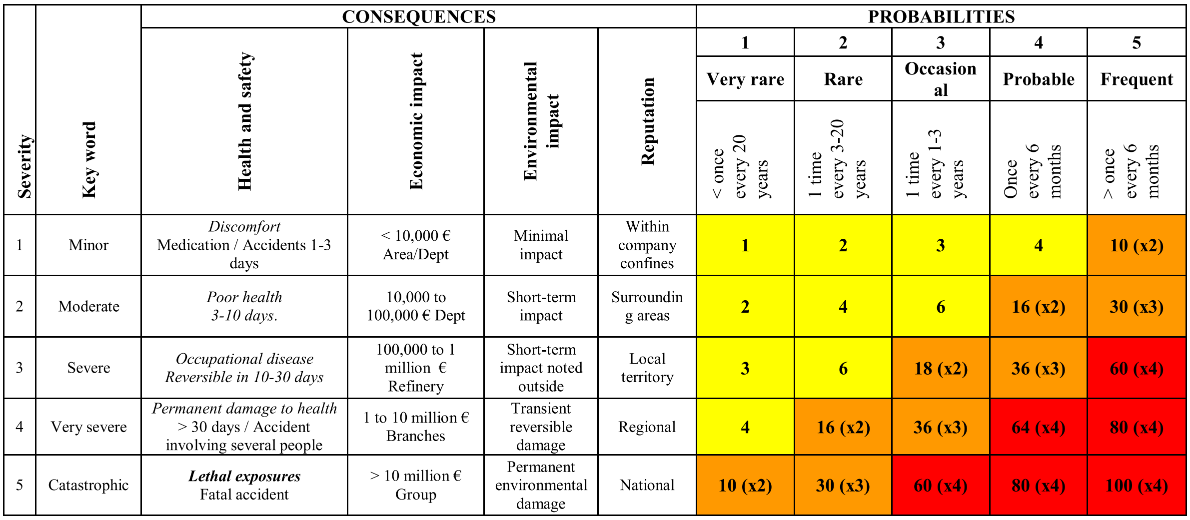
The risk score which should be considered in the case of different consequences is the highest score found among the items measured. There is also a multiplication factor f in the matrix which allows the risk to be specified numerically on a scale of 1 to 100. This index, of a numerical type, was changed to a nominal value by dividing it into three categories: **LOW RISK, MEDIUM RISK** and **HIGH RISK**. LOW-RISK value was assigned if the risk index was less than or equal to 6; MEDIUM RISK for a risk index between 6 and 36 and finally HIGH RISK if the risk index was greater than 36.

3.1.5. Human corrective actions

Each adverse event must be investigated thoroughly and action taken to reduce the risk of recurrence. The Refinery analyst must identify the Human Corrective Action which was considered necessary in order to avoid repetition of the same event in the future. The list of Human Corrective actions (Table 4) has been identified by analysing the corrective actions historically carried out in the refinery.

The proposed corrective actions take into consideration the roles and responsibilities of personnel involved in the management of major hazards at all levels in the organization. Some actions consider the identification of training needs of the personnel and the provision of

Table 3
Risk assessment matrix.



Severity	Key word	CONSEQUENCES				PROBABILITIES				
		Health and safety	Economic impact	Environmental impact	Reputation	1	2	3	4	5
						Very rare	Rare	Occasional	Probable	Frequent
						< once every 20 years	1 time every 3-20 years	1 time every 1-3 years	Once every 6 months	> once every 6 months
1	Minor	*Discomfort* Medication / Accidents 1-3 days	< 10,000 € Area/Dept	Minimal impact	Within company confines	**1**	**2**	**3**	**4**	**10 (x2)**
2	Moderate	*Poor health 3-10 days.*	10,000 to 100,000 € Dept	Short-term impact	Surrounding areas	**2**	**4**	**6**	**16 (x2)**	**30 (x3)**
3	Severe	*Occupational disease Reversible in 10-30 days*	100,000 to 1 million € Refinery	Short-term impact noted outside	Local territory	**3**	**6**	**18 (x2)**	**36 (x3)**	**60 (x4)**
4	Very severe	*Permanent damage to health* > 30 days / Accident involving several people	1 to 10 million € Branches	Transient reversible damage	Regional	**4**	**16 (x2)**	**36 (x3)**	**64 (x4)**	**80 (x4)**
5	Catastrophic	***Lethal exposures*** Fatal accident	> 10 million € Group	Permanent environmental damage	National	**10 (x2)**	**30 (x3)**	**60 (x4)**	**80 (x4)**	**100 (x4)**

Table 4
Human corrective actions.

Human corrective actions
Interview with the injured person
Safety talk
Training on the use of PPE
Intensify the training program
Internal testing or assessment of modifications
Identify extra PPE for the workers
Verbal warning
Written warning to the employee
Disciplinary sanction for the employee
Penal sanctions for the external contractor firms/operators
Control of external operator/contractors

Table 5
Time-scale for carrying out work order and corrective actions analysis.

Risk values	Priority
Risk = High	Analysis must be carried out immediately
Risk = Medium	Analysis must be started within 48 hours
Risk = Low (between 4 and 6)	Analysis must be started within one week

the training so identified, the involvement of employees and, where appropriate, subcontractors. Other corrective actions regard the adoption and implementation of procedures and instructions for safe operation, including the maintenance of the plant, processes, equipment and momentary stoppages.

The monitoring actions regard the adoption and implementation of procedures for the ongoing assessment of compliance with the objectives set by the operator's major-accident prevention policy and SQE management system, as well as the mechanisms for investigation and taking corrective action in case of non-compliance.

The procedure showed in Fig. 1 and in particular, the identification of human error causes and the Performance Shaping Factors helps the analyst to identify the best corrective action and assign a priority to each possible action.

The Risk Index (real or potential according to which one is the highest) referred to the adverse event identified through the use of the risk matrix and reported in the accident reporting system modules of the refinery, determines the priorities, i.e. the deadline for starting analysis of the event and maintenance plan according to the criteria shown in Table 5. This table defines the timescale for carrying out work orders and corrective actions analysis. Following the prioritization, it is then necessary to ensure the control of the scheduled time for the execution of the follow-up plan, with all the corrective actions.

The procedure is based on the concept that, by identifying the causes and determining corrective action, the analysis of undesired events leads to the introduction of a continuous improvement process, which is typical of management systems.

In order to evaluate how effective a corrective action can be, it is possible to recalculate the Risk Index considering how the corrective action would improve the risk value.

3.1.6. *Human factor risk analysis*

A Human Factor Risk Analysis is performed monthly, based on the result of the daily reports of adverse events loaded on CMMS. This analysis, carried out directly by the Human Factor Risk Group, aims at providing the refinery decision makers with risk reduction recommendations to mitigate the potential for human error. Moreover, this analysis aims at identifying the Root Causes of the event, that is to say, which element of the human factor did not work correctly, creating the circumstances which led to the human error. Why was that procedure or condition present?

Using association rules technique, this analysis investigates relationships among all variables defined during the HFRM procedure: typology of adverse events, the work situation or the way in which the event occurred, date of the event, the plant area where the event occurred, the part of the body injured, Human error causes, PSFs involved and their rating scales, risk and corrective actions.

3.1.6.1. Association rule approach. Agrawal et al. [33] introduced association rules for discovering regularities between products in large-scale transaction data recorded by point-of-sale systems in supermarkets. For example, the rule {butter,bread}⇒{milk} found in the sales data of a supermarket would indicate that if butter and bread are bought, customers also buy milk. Today, association rules are employed in many other application areas (Continuous production, civil and construction, bioinformatics, etc..). Following the original definition of Agrawal et al. [33] the problem of association rule mining is defined as: let $I = \{i_1, i_2, , \ldots, i_n\}$ be a set of n binary attributes called items, and let $D = \{t_1, t_2, \ldots, t_m\}$ be a set of transactions called the database. Each transaction in D has a unique transaction ID and contains a subset of the items in I. A rule is defined as an implication of the form A→B, where A and B are known as item sets, and $A, B \subseteq I$, $A \cap B = \emptyset$. Agrawal et al. [33] considered each rule composed by two different sets of items, called item-set (A and B).

Hence, A is named the antecedent or left-hand-side (LHS) and B is the consequent or right-hand-side (RHS). Moreover in order to select rules of interest, three common metrics (support (2), confidence (3) and lift (4)) are defined for measuring association between the antecedent and the consequent.

$$Support = \frac{\#\{LHS \cup RHS\}}{\#\{all\ records\}} \tag{2}$$

$$Confidence = \frac{Support\ \{LHS \cup RHS\}}{Support\ \{LHS\}} \tag{3}$$

$$Lift = \frac{Support\ \{LHS \cup RHS\}}{Support\ \{LHS\}\ x\ Support\ \{RHS\}} \tag{4}$$

Hence, the "Support" indicates how frequent combination of itemsets occurs in the dataset for an alternative. In contrast, the confidence is equivalent to the conditional probability, the probability of finding the RHS of the rule in transactions under the condition that these transactions also contain the LHS. Furthermore, the lift tells us whether the antecedent and the consequent are independent (zero), positively correlated (above unity), or negatively correlated (below unity). Many algorithms for generating association rules have been proposed. The most used algorithms for mining frequent itemsets are Apriori, Eclat and FP-Growth [34]. There is no fundamental difference between these algorithms if only extracting a small number of rules [35]. In this work the most representative Apriori algorithm has been used. Apriori is a seminal algorithm for finding frequent itemsets using candidate generation [36]. Apriori algorithm assumes the anti-monotonicity of itemsets: if an itemset is not frequent, any of its superset is never frequent. By convention, Apriori supposes that items within a transaction or itemset are sorted in lexicographic order. Therefore, let the set of frequent itemsets of size k be A_k and their candidates be B_k. Apriori first analyses the database and searches for frequent itemsets of size 1 by accumulating the count for each item and collecting those that satisfy the minimum support requirement. The algorithm then iterates according to the following three steps and extracts the most frequent itemsets.

1. Generate B_{k+1}, candidates of frequent itemsets of size k + 1, from the frequent itemsets of size k.
2. Scan the database and calculate the support of each candidate of frequent itemsets.
3. Add those itemsets that satisfies the minimum support requirement to A_{k+1}.

4. Human factor risk analysis methodology application

The present analysis was carried out at the end of December 2015. Data concerning 2076 cases of adverse events which occurred in the decade 2005–2015 were collected at the refinery. The Human Factor Risk group reorganized in detail all the data for each adverse event contained in the refinery data set. As regards the problems related to the application of the proposed technique, the group of experts, created for this study, worked for 2–3 months essentially to overcome difficulties in the data collection phases and in order to find those rules which are characterized by the best *risk values*. For each adverse event, and in particular on the basis of the "description of the event", it was necessary to elaborate the information required for the analysis and the classification of the event.

The codification and frequency for information fields for corresponding factors are shown in Table 6.

Association Rule Mining is performed on the data set (2076 cases) and 52 items in the data set (categorical variables) using the Apriori algorithm implementation from the arules package for R. We mine for different groups of rules whose consequent contains the variable Risk Index and all Performance Shaping Factors. In this section, only the results obtained for Risk Index = "High" and PSFs = "Training level" will be shown as they are considered the most important.

Table 6
Factors and items codification and frequency distribution.

Factors	Items	Frequency
Adverse event typology	Near miss	949
	Accident or Injury	263
	Operating accident	341
	Environmental accident	523
Plant area	Topping	210
	Catalytic	148
	Reforming	59
	Isomerization	214
	Vacuum	108
	Visbreaking	174
	Thermal cracking cycle	207
	Auxiliary oxygen production	287
	Gas washing	241
	Sulphur recovery	39
	Effluent treatment	114
	Air separation unit	275
Human error cause	Operation carried out without authorization	131
	Necessary operation/procedure was forgotten	74
	Incorrect choice of raw material	148
	Lack of precision/inappropriate speed of performance/haste	170
	Warning given incorrectly/insufficiently/to the wrong person	153
	PPE (Personal Protective Equipment) used badly/faulty	127
	Inadequate knowledge of regulations and procedures	140
	Made inoperative a control system	61
	Incorrect loading/lifting/substitution of equipment	158
	Incorrect/inappropriate use of equipment/appliances	407
	Incorrect position or posture during the developed activity	122
	Maintenance/action/operation carried out on equipment in run	50
	Bad habits	140
	Lapse of concentration/detrimental behavior	195
Performance Shaping Factors (PSFs)	Training level	481
	Available time for task execution	466
	Attention towards suppliers/stakeholders	209
	Human-machine interface	278
	Quality of Information (lack of communication)	93
	Company safety culture	268
	Level of Experience	226
	Lack of Supervision	251
Risk Index	Low	940
	Medium	813
	High	323
Corrective actions	Interview with the injured person	501
	Safety talk	177
	Training on the use of PPE	136
	Intensify the training program	274
	Internal testing or assessment of modifications	82
	Identify extra PPE for the workers	118
	Verbal warning	354
	Written warning to the employee	111
	Disciplinary sanction for the employee	63
	Penal sanctions for the external contractor firms/operators	13
	Control of external operator/contractors	247

Table 7
Consequent Risk Index = "High", ranking of the top 5 rules.

N.	Rule	Support	Confidence	Lift
1	Plant area="Air Separation Unit" → Risk Index="High"	0.082	0.619	3.979
2	Adverse event typology="Accident or Injury" → Risk Index="High"	0.078	0.615	3.957
3	PSF="Company safety culture" → Risk Index="High"	0.071	0.606	3.899
4	Plant area="Air separation unit", PSF=" Lack of supervision" → Risk Index = "High"	0.063	0.605	3.893
5	PSF="Available time for task execution" → Risk Index="High"	0.065	0.602	3.872

Table 8
Consequent PSFs = "Training level", ranking of the top 5 rules.

N.	Rule	Support	Confidence	Lift
1	Corrective action="training on the use of PPE for the workers" → PSF="Training level"	0.058	0.819	3.535
2	Human error cause="Inadequate knowledge of regulations and procedures" → PSF="Training level"	0.061	0.801	3.459
3	Human error cause="PPE (Personal Protective Equipment) used badly/faulty", Corrective action="training on the use of PPE for the workers" → PSF="Training level"	0.052	0.782	3.375
4	Plant area="Auxiliary oxygen production" → PSF="training level"	0.087	0.629	2.716
5	Adverse event typology="Operating accident", Human error cause="Inadequate knowledge of regulations and procedures" → PSF="Training level"	0.054	0.613	2.646

As Association Rule usually results in a large number of association rules, the notion of rule interest (Tew et al. [37]) is important when evaluating the generated rules. In order to discover the rules, minimum thresholds for support and confidence need to be specified. Numbers of association rules generated are inversely proportional to the threshold support and threshold confidence. There is no established criterion for selecting threshold values for support and confidence. Different studies considered different threshold support and confidence values as per the availability of a number of data points and achievement of strong rules (Verma et al. [38]). In the refinery case study, the threshold support and confidence values equal to 0.05 and 0.6 respectively have been considered, along with a lift value greater than one. The starting support threshold was set to 0.1 (10% of all cases) but had to be gradually decreased in order to increase the number of rules for later inspection. The support threshold had to be further decreased because the data set was imbalanced in favor of medium and low risks, while the high risk was only present in 323 cases (15.6%). The generated rules are ranked to facilitate the identification of the most relevant relationships between variables. Moreover, in order to avoid repetitions in rules, redundant results have been excluded from the study. A rule r in R is said to be redundant only if a rule or a set of rules S where S in R, possess the same intrinsic meaning of r.

We obtained 38 rules considering Risk Index = "High" as a consequent or right-hand-side (RHS) and 42 rules considering PSFs = "Training level" as a consequent. These rules have satisfied the minimum support (0.05) and minimum confidence (0.6) along with lift values greater than one. Rules consisting of higher lift (greater than one) values are stronger and more interesting. Tables 7 and 8 show the top 5 rules for Risk Index = "High" and PSFs = "Training level" respectively.

4.1. Discussion

The Human Factor Risk analysis carried out in this application was planned as a dynamic process and can be repeated systematically. Many rules have been developed and used by Refinery decision makers. In the previous section, we used two tables and ten rules for explaining the Human Factor Risk Analysis method. These rules refer to the two most important consequent or right-hand-side (RHS): "high risk" events and "training level" (which is the most frequent Performance Shaping Factor).

The Human Factor Risk analysis demonstrates that causes of human error and high-risk events were to be found in a complex of factors. As a result, control of the most important factors must improve and a greater effort should be made to reduce the risk of future events.

To sum up and explain the results obtained with high risk as a consequent (Table 7) it is possible to state that:

- The first and fourth rules of Table 7 mean that the Air Separation Unit is the plant where one is most likely to have high-risk events, while the lack of supervision is the Performance Shaping Factor. Analyzing this result by one-to-one interviews with the Air Separation Unit operators it is possible to highlight that they considered the area to be a remote one. This is due to a lack of control from the area supervisors and could have conveyed the sensation that the process they were performing was a not very important one (it was not part of the normal manufacturing process). This effect could have been avoided by directly controlling the area, even during the area supervisor's daily patrol. The lack of supervision, as important PSFs, was also highlighted by Zhou et al. [39] analyzing the human factors in large-scale hydropower-construction-projects. They assessed the human factors by the methods of the decision-making trial and evaluation laboratory (DEMATEL) and the analytic network process (ANP).
- The second rule means that Accident or Injury events are most likely to be the reason for high-risk adverse events. This result is essentially due to the consequences connected to Injury events that are often severe or very severe.
- The third rule highlights that high-risk events are most likely to have happened due to "Company safety culture" as a PSF. During this study, it was possible to notice that operator errors in many cases were related to managerial errors due to "lack of safety culture". Operator motivation for a positive approach to safety is the result of the personal involvement of general management in safety-related activities and in training programs, sponsoring the company internal objectives about safety and guiding the event investigation towards problem-solving rather than towards finding the "guilty" party. The daily safety report that the area supervisor was expected to compile was just seen as a bureaucratic routine in the organization culture, meaning that the form and the attention paid to that tool could be changed in order to use it as a proper method of prevention. The safety management system that the company had, was mainly focused on meeting the legal requirements; according to Chen et al. [40], a safety culture in a high hazard process plant is part of the integrated management. It could be built up over time if the SQE system is tailored to the reality which is actually applied and if the management of the company is directly involved. The problem of the technician that is handling the hazardous substance should be considered as part of his job.
- The fifth rule signifies that high-risk events are most likely to have happened due to the short time available for the task execution as a PSF. One-to-one interviews, about this point, highlighted that the operators were under time pressure especially when they were wait-

ing for new staff to join the crew, and they wanted to enable them to start from the beginning of the process. Being under time pressure is one of the environmental conditions that raises error probability. In the process industry, the production should be scheduled considering all the possibilities to avoid restricted time conditions that could lead to criticality.

Analyzing the results obtained with Training level as a consequent (Table 8) it is possible to state that:

- The first and the third rule of Table 8 means that "training level" PSF is most likely to have happened due to Human error cause="PPE (Personal Protective Equipment) used badly/faulty" while the Corrective action is "training on the use of PPE for the workers". These rules allow the Refinery to identify the human error and corrective action connected to the PSF = "Training level". The company tried to improve communication with workers, giving them adequate knowledge of regulations and procedures about PPE. Moreover, to mitigate the consequence of negligence or misconduct by the workers the most important action taken was a constant training and monitoring of the appropriate use of Personal Protective Equipment (PPE).
- The fourth rule means that "training level" PSF is most likely to have happened when the plant area is "Auxiliary oxygen production". Analyzing this rule by one-to-one interviews with Auxiliary oxygen operators, we discovered that external companies commissioned to maintain the cryogenic pumps, very often used by young operators or seasoned workers without experience regarding refinery procedures. To overcome this problem, for external operators a specific training cycle has been planned, as well as more frequent meetings with the refinery supervisor regarding refinery standards. According to Wilson [2], the cultural solicitation of workers (internal or external) in order to involve them in solutions and risk management is one of the most effective strategies for controlling root causes.
- The second and fifth rules highlight that "Training level" PSF is most likely when the "Inadequate knowledge of regulations and procedures" is the human error cause and "Operating accidents" is the adverse event typology. It is also observed that operating accidents occur mainly during group working conditions, implicating lack of alertness and awareness. This can be improved by spreading awareness of safety culture among workers. Training should be provided mainly to new employees and temporary workers who do not have adequate experience, or who are not familiar with the new working environment. Two factors are specifically relevant in this context and must be guaranteed: (1) respect for the safety legislation in force; (2) training and information for workers. The data often lacks information and training activities to inform the workers about all Italian safety laws (i.e., Law 81/2008) and about the correct working procedures which guarantee safer conditions.

5. Conclusion

The purpose of this study was to develop a procedure for investigating and identifying human factors risks and generating association rules for adverse events occurring in a refinery, as well as suggesting preventive and safety measures to prevent or minimize high-risk events. The analysis carried out was of great use to the refinery for providing feedback on the adverse events data collected over several years. If the information obtained from reports, drawn up after an adverse event and subsequently developed by the "Safety & Quality" and "Reliability" Departments", is not periodically correlated and classified, it risks becoming a mere legal requirement which does not provide possible guidelines for the future.

Moreover, the Human Factor Risk Management procedure proposed will not completely change the current procedure in the oil refinery. It is introduced as an addition to the present one. Therefore, it has to be used not only for off-line error prevention to ensure a robust system, i.e. a system in which the occurrence of a human error is impossible but also for on-line error prevention to ensure a tolerant system, i.e. a system in which human error can appear. High-Risk conditions appear to be dependent on plant area and workers' behavior and awareness, although the factor of safety culture in the workplace also plays a part. It is, therefore, necessary to focus more on supervision and the respect for refinery regulations to reduce the risk factors as much as possible.

The management of human factor has a strategic importance within a refinery from an organizational, engineering and economic point of view. The determination of a procedure, that allows a methodical and possible automatic approach to management of human factor data, can make substantial improvements in the organization of work and in the decision-making processes. It is important from an engineering point of view to focus the efforts on the aspects of the problem, where it is possible to intervene in order to optimize the general situation. Within the same company, the different types of plants require different needs and attention due to the "history" of each specific unit, which begins with the commissioning and start-up steps. It should be mentioned that, despite the initial wariness of the refinery staff, the multidisciplinary approach was greatly appreciated by all the members of the Human Factor Risk group. The definition of variables and the understanding of rules that can help "decision-makers" were possible only thanks to the combination of multidisciplinary skills. This solution allowed the refinery risk managers: (1) to combine academics' theoretical knowledge with the day-to-day problems of a high-risk company; (2) to investigate the events in depth so as to arrive at "all" possible connections and causes; (3) to identify solutions that are really applicable to the production reality analyzed.

This paper demonstrates that Association rules are a powerful alternative to the frequently used traditional parametric techniques. A large number of possible uses for this non-parametric approach are stressed, including all types of adverse events in any industrial field. Association rules are appropriate whenever the aim is to understand the problem being examined as thoroughly as possible in order to make the best decisions and choose the best ways of making improvements. The use of association rules technique may also be considered a preliminary exploratory technique for evaluating the factors influencing the most dangerous situations. However, it must not be seen as an attempt to supplant traditional statistical and mathematical techniques, but as a complementary method to be integrated into this type of analysis. In this context, a further development of this work can be focused on the integration of Bayesian Network methods in order to model uncertain and complex domains such as human factors and risk management in a refinery.

Appendix 1

Table 9 collects some terms shown in Fig. 1.

Table 9
Definitions.

Item	Definition
Critical Item	Item identified with specific operational functions. Its malfunctioning compromises the operations of the plant in which it is used; in other words the unavailability of this equipment or device has implications for safety or may cause plant shutdown or may prevent the loading of products via land or sea.
Bad item	An item broken down within the year or defined as such because of its technical functions.
Near miss	Events which have been a source of risk or danger, potentially provoking injuries and accidents;
Operating Accidents	Operating accidents are those events which resulted in operational targets not being reached following “upsets” or “poor functioning”.
Environmental Accidents	Environmental accidents are those events which have led to a lack of conditions which respect the environment.
Injuries	Injuries according to Italian Law (Art.2 DPR 1124 of 20/6/65)
Shutdown	Total shutdown of operations in a plant due to any type of anomaly.
Slowdown	Reduced working capacity of the plant, less than 75% of the expected value.

Appendix 2

Table 10.

Table 10
Initial list of PSFs.

Performance Shaping Factor	Source
Training level	Kecklund and Svenson [41]; Kirwan [42]; Cacciabue [21]; DiMattia et al. [16]; Grozdanovic [43]; Khan et al. [19]; Skogdalen and Vinnem [44]; Tu [45]; Norazahar et al. [46]; Calixto et al. [11]; Groth et al. [53]; Mitchell et al. [47]
Design of display boards	Grozdanovic [43]; Tu [45]
Design of control panels	Grozdanovic [43]; Tu [45]
Complexity of procedures	Grozdanovic [43]; Skogdalen and Vinnem [44]; Tu [45]; Calixto et al. [11]; Norazahar et al. [46]; Groth et al. [53]
Motivations/predisposition	Grozdanovic [43]; Kariuki and Lowe [49]; Mohaghegh and Mosleh [50]; Tu [45]; Martins and Maturana [23]; Pasman and Rogers [51]
Illumination	Grozdanovic [43]; Tu [45]
Level of experience	Kirwan [42]; DiMattia et al. [16]; Khan et al. [19]; Tu [45]; Mitchell et al. [47]
Equipment and tool condition	Tu [45]; Norazahar et al. [46]; Mitchell et al. [47]
Work environmental condition	Kecklund and Svenson [41]; Kariuki and Lowe [49]; Tu [45]; Mitchell et al. [47]
Lack of supervision	Skogdalen and Vinnem [43]; Tu [45]; Norazahar et al. [46]
Available time for task execution	Kirwan [42]; Skogdalen and Vinnem [44]; Calixto et al. [11]; Pasman and Rogers [51]; Groth et al. [53]
Quality of information (lack of communication)	Kirwan [42]; Skogdalen and Vinnem [44]
Task organisation	Kirwan [42]; Mitchell et al. [47]
Task complexity	Kirwan [42]; DiMattia et al. [16]; Khan et al. [19]; Skogdalen et al. [48]; Skogdalen and Vinnem [44]; Groth et al. [53]
Stress	DiMattia et al. [16]; Khan et al. [19]; Skogdalen and Vinnem [44]; Calixto et al. [11]; Groth et al. [53]; Mitchell et al. [47]
Factors associated with the muster initiator (Event Factors)	DiMattia et al. [16]; Khan et al. [19]
Factors associated with the weather/environment (Atmospheric factors)	DiMattia et al. [16]; Khan et al. [19]
Physical conditions	Kariuki and Lowe [49]; Mohaghegh and Mosleh [50]; Martins and Maturana [23]; Norazahar et al. [46]; Mitchell et al. [47]
Personality and intelligence	Kecklund and Svenson [41]; Martins and Maturana [23]; Norazahar et al. [46]
Human-machine interface	Kariuki and Lowe [49]; Skogdalen and Vinnem [44]; Calixto et al. [11]; Groth et al. [53]
Fitness for duty	Kariuki and Lowe [49]; Calixto et al. [11]; Groth et al. [53]
Excess of rules and regulations	Cacciabue [21]
Comfort of working contexts	Cacciabue [21]
Unclear rules for communication	Cacciabue [21]; Skogdalen et al. [48]; Skogdalen and Vinnem [44]; Pasman and Rogers [51]
Psychological safety climate	Mohaghegh and Mosleh [50]
Lack of skills	Kariuki and Lowe [49]; Mohaghegh and Mosleh [50]; Mitchell et al. [47]
Ability	Mohaghegh and Mosleh [50]
Organisational factors (Work load)	Skogdalen et al. [48]; Skogdalen and Vinnem [44]; Pasman and Rogers [51]; Mitchell et al. [47]
Fatigue	Skogdalen and Vinnem [44]; Mitchell et al. [47]
Company safety culture	Knegtering and Pasman [52]
Attention towards suppliers/stakeholders	Knegtering and Pasman [52]
Procedural knowledge	Kariuki and Lowe [49]; Martins and Maturana [23]
Teamwork	Martins and Maturana [23]
Quality of sleep	Martins and Maturana [23]
Threats (of failure, loss of job)	Martins and Maturana [23]

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