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Human reliability analysis of the Tokai-Mura accident through a THERP–CREAM and expert opinion auditing approach ☆

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ABSTRACT

This paper presents a human reliability analysis (HRA) model that allows the incorporation of features related to facility conditions to determine human error probabilities (HEP) used in probabilistic safety analyses of process plants. We present an approach to show the predominance of human factors as an accident cause, as well as existing methodologies for HEP determination and their deficiencies in incorporating socio-technical elements that influence them. Such elements are: inappropriate design, training, procedures, communication, safety culture, management in the production process changes, emergency planning, accident investigation, environmental factors, maintenance workload and human–system interface. A mathematical model is proposed to incorporate these elements taking into account their contribution weights as well as measuring their degree of implementation in the plant. This creates a factor that can modify existing HEPs, giving values that better reflect plant reality. The model was applied to the accident that occurred in 1999 in Tokai-Mura, Japan. The modified HEP was 2 times greater than the nominal HEP. This shows that considering organizational factors thoroughly allows for a more realistic plant behavior modeling in face of abnormal events.

1. Introduction

The increasing globalization of world economy is turning the environment of organizations ever more complex, where scenario changes occur in a dynamic, nonlinear, unpredictable and fast-paced way, requiring organizations to have a continuing need for changes to adapt to new success conditions. Proper management of opportunities and threats created by these scenario changes have come to constitute a key factor for competitiveness and survival of organizations. A great improvement of technological aspects in comparison with human and organizational factors has been observed in recent decades. This mismatch is evident if one looks at accident histories at facilities that handle hazardous technologies, which shows that organizational factors have an increasing importance on accident causes (Hollnagel, 2004).

When compared to technological factors, human and organizational factors are characterized by their multidimensional nature and complexity due to nonlinear interactions that influence their behavior. A variety of quantitative and qualitative methods have been proposed to incorporate these factors into reliability calculations, but not as yet successfully, Papazoglou et al. (2003).

People are the common theme within organizations. They are fundamental components that hold complex systems together. Safe operations rely, among others, on their competence to respond quickly and appropriately to emergency situations. However, humans are fallible: human error has been a contributing factor in all major accidents, Sirrett (2013).

Human reliability analysis techniques, which allow quantification of human error probabilities (HEPs) used in nuclear installations, are THERP (Swain and Guttman, 1983), MERMOS (Bieder et al., 1998), CREAM (Hollnagel, 1998) and ATHEANA (NRC, 2000), in general. These HEPs are also used in quantitative risk analyses in the chemical, petrochemical, and aerospace fields, and in semi-quantitative risk analyses, as, for example, in LOPA (CCPS, 2001) in chemical process industries.

In industries dealing with hazardous technologies one can refer to some regulations that induce them to anticipate this learning,

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Nomenclature

ABIQUIM	Brazilian Association of Chemical Industries
AHP	Analytical Hierarchy Process
ATHEANA	A Technique for Human Event Analysis
CCPS	Center for Chemical Process Safety
CREAM	Cognitive Reliability and Error Analysis Method
CSB	Chemical Safety Board
EF	error factor
HEP	human error probability
HF	human factors
HRA	human reliability analysis
ILO	International Labor Organization
JCO	Tokyo Electric Company
LOPA	Layer of Protection Analysis
MERMOS	Méthode dÉvaluation de Réalisation des Missions Opérateur pour la Sûreté
OGP	International Oil and Gas Producers Association
OSHA	Occupational Safety and Health Administration
THERP	Technique for Human Error Rate Prediction

such as the Seveso II Directive (1996), used in Europe, OSHA regulations (used in the U.S.) and the 174 Resolution of the International Labor Organization (ILO 174). These regulations seek to establish risk quantification in order to offer society a numerical risk acceptability criterion. These risk-based regulations provide figures that allow one to decide whether to go ahead with plant designs.

In this context, one can consider that proposals to quantify human errors should be adapted to the conditions of each facility, for only in the microcosm is it possible to treat nonlinearities that bring complexity to the problem. This path enables to point in advance safety deterioration and the set of factors that are contributing to it.

The aforementioned techniques incorporate modifying factors of human performance to HEPs, which are mostly ergonomic, still without taking into account socio-technical factors relating to individuals and safety management. A thorough discussion on these issues can be found in Alvarenga et al. (2014).

As a way to fill the need for a model that allows the incorporation of contributing socio-technical elements to human error and in this sense help provide more realistic human error probabilities, we propose a model which takes into account influencing factors identified in the oil industry (OGP) and also the experience gained from operational incidents and accidents besides an auditing procedure. These influencing factors are to be taken into account in order to consider new factors that have not yet been considered in human error probability evaluation techniques. Also the interaction of these factors is addressed. The purpose of adding an auditing process is to consider the plant capability to respond to these factors. It is worth mentioning here that an analysis of one of the human errors in the Three Mile Island accident was performed by means of a hybrid THERP–ATHEANA approach in order to shed some light on the application of HRA techniques (Fonseca et al., 2013).

The purpose of this paper is to present the model discussed in the last paragraph. This paper is organized as follows: the proposed model is described in Section 2 and Section 3 presents the case study developed for the accident at the fuel element facility of the Tokyo Electric Company (JCO) in Tokai-Mura, Japan (Furuta et al., 2000). Conclusions reached and recommendations are presented in Section 4.

2. Description of the proposed HEP quantification model

2.1. Introduction

HEP assessment starts by considering a known human reliability technique for obtaining basic HEPs. Two natural candidates are THERP (Swain and Guttman, 1983) and CREAM (Hollnagel, 1998) because among other features, they have quantitative information to start with. However, the effort to adapt these basic HEPs to a given plant presents a series of shortcomings. For example, the performance shaping factors employed in THERP fail to treat many organizational aspects that are relevant, Alvarenga et al. (2014). A similar issue may be found about CREAM common conditions. The US Nuclear Regulatory Commission has issued a set of 16 main performance shaping factors (NRC, 2005, 2006) among which only 3 are of an organizational nature. Likewise, among the 11 common conditions identified in CREAM, only 3 are of an organizational nature, that is, Adequacy of organization, Working conditions, and Number of simultaneous goals. In this sense, alternatives have been sought for in order to modify basic HEPs in a more realistic way.

The foundations of the model proposed in this paper may be found in Papazoglou et al. (2003), Kariuki (2007) and Sousa et al. (2007). Particularly, the model proposed by Kariuki (2007) is the most suitable for understanding the foundations of our model.

The proposed model starts from existing HEPs and introduces factors that allow for reflecting actual plant conditions (Fig. 1). It is seen from Fig. 1 that we start with a reference parameter (the nominal HEP represented by a confidence interval defined by the 5th and the 95th percentiles, in general) and modify it in levels. Notice that two levels may be identified: the first level addresses the assessment of 12 elements influence and it generates Grade 1, which shows the relative importance of an element in relation to the remaining ones.

The second level is a plant-specific level (shaded area in Fig. 1) and it generates two grades, Grade 2 and Grade 3. Grade 2 gives the weight of each factor or element based on external expert opinion and Grade 3 takes into account the incidence weights (that is, operational experience, when available). Notice that each grade gives different attributes that do not overlap.

The auditing process also does not overlap because the purpose of the auditing process is to explicitly unravel the plant state.

Finally an adjusted HEP is obtained by taking into account the three grades and the auditing process.

2.2. Level 1 quantification

The OGP model (OGP, 2005) for the 12 elements displayed in Fig. 2 identifies three domains for human factors: facilities and equipment, people, and management systems. These domains overlap and cannot be separated or removed from the model.

The facilities and equipment domain includes consideration of physical characteristics and work space, design and maintenance of equipment, and reliability.

The people domain includes consideration of individual attributes, skills, perceptions, and factors relating to fitness, stress, and fatigue. Some attributes, such as personality, cannot be changed, while other skills and attributes can. Computers and control

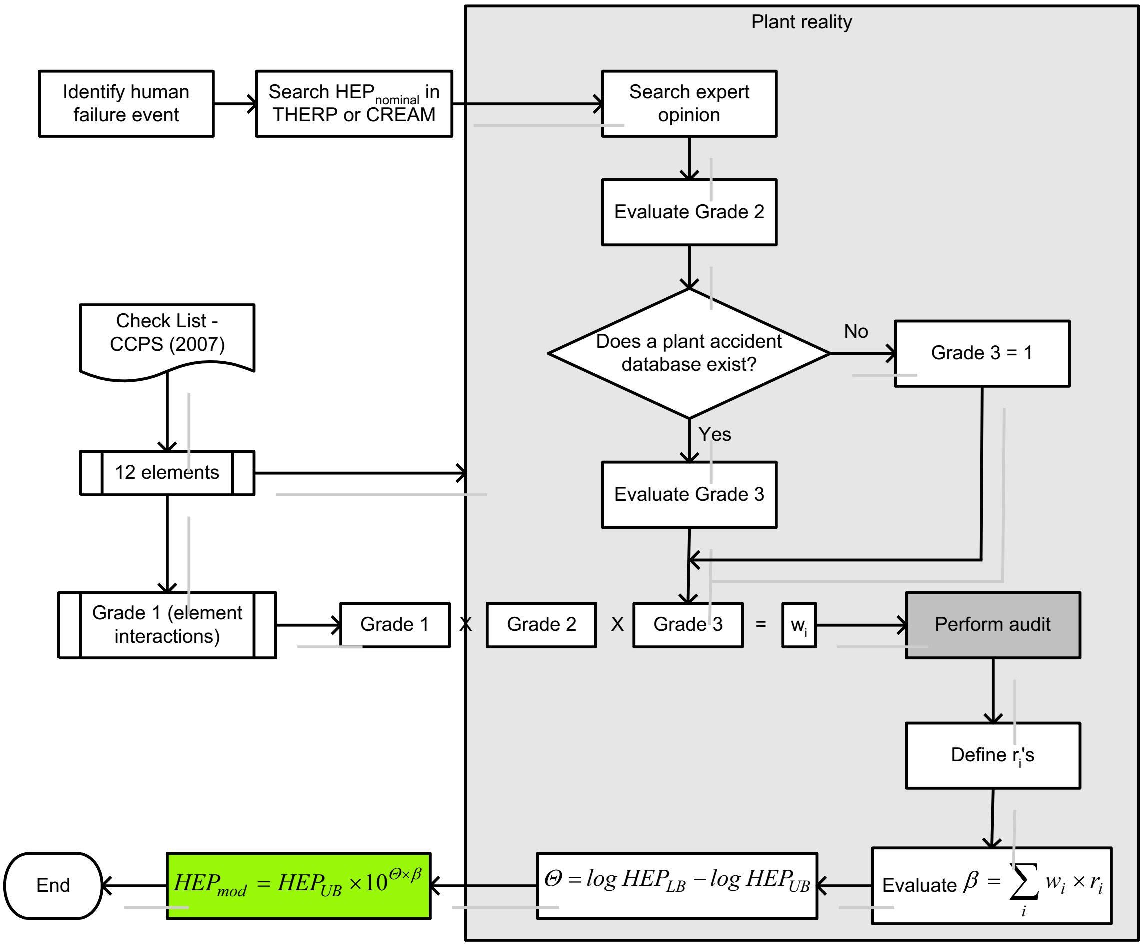

Fig. 1. Flowchart of the proposed model.

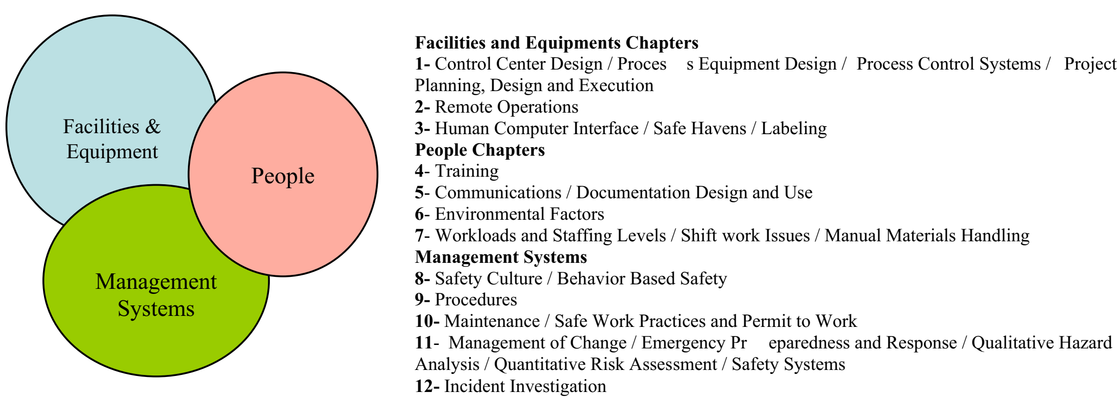

Fig. 2. Human factors model for a process plant. Adapted from OGP (CCPS, 2007).

systems play a major role in the safe and reliable operation of plants in the process industries. The interaction between humans (people domain) and computers (facilities and equipment domain) is one aspect of the overlapping between domains.

The management systems domain provides the framework under which work is carried out. It includes procedures, training, process safety related work systems, and aspects of safety culture. Overriding all of these domains is the cultural and working environment. There are national, local, and workplace cultures as well as social and community factors.

Particularly, the ‘safety culture’ element deserves a special comment. According to CCPS (2007) if one considers the features associated with a positive safety culture this implies, for example, good plant design, working conditions and housekeeping and also perception of low risk due to confidence in engineering systems (in what concerns hardware). On the other hand, taking management systems into consideration, a positive safety culture means, for example, confidence in safety rules, procedures and measures. If one considers people, a positive safety culture means, for instance, high levels of employee participation in safety and also people trust in workforce to manage risk. This, again, illustrates dependencies between the 12 elements of Fig. 2.

The first step is to analyze the interactions between the 12 elements adopted by means of paired comparisons.

The twelve elements have been set by starting with the OGP (International Association of Oil & Gas Producers) model, OGP (2005), CCPS (2007) and taking into account the authors' experience on the management of process safety in chemical and nuclear plants. The twelve elements give a good connection between human factors and plant life cycle and include best practices of project management and workforce development, besides being an efficient auditing tool. Its results may be an indicator of the organization membership degree to a management model of human and organizational factors. The elements proposed by OGP were grouped, as well as the human factors questionnaire implemented in this work for the auditing process.

The proposed methodology requires that the analyst be familiar with the plant control room and the surrounding area. A qualitative analysis must be performed by which plant control and procedures are analyzed and an extensive discussion with operators is carried out to identify working conditions, their practices and attitudes in plant management and implementation of normal and emergency operating procedures.

As mentioned earlier, Grade 1, which measures the relative importance of the factors influence, is achieved through an array of relationship factors by which it is possible to analyze the distribution and intensity of factor relationships.

Kariuki's model starts by implementing an Analytical Hierarchy Process (AHP) (Saaty, 2000) in HEP assessment because, due to the uncertainty in nominal HEPs (for example, THERP's 90% interval from lognormal distributions), one may have a wide range HEP for which a lower and an upper bound are estimated. As the purpose is to correct this HEP in a realistic way, one should obtain what Kariuki calls a human factor (HF) quality index.

2.3. Level 2 quantification

Grade 2 measures the weight of each factor or element influence (Fig. 2) through the elicitation of expert opinion (Ayyub, 2001). Ten experts attributed a degree 1–5, where 1 is the lowest contribution degree and 5 is the largest one to the importance of each of the factors shown in Fig. 2.

Grade 3 represents the incidence weights of factors or elements as root causes or contributors, being established from an analysis of abnormal events [incidents, accidents and near misses, CCPS (2000), IAEA (2007)] in the plant, which shows the number of times that each element contributed as a root cause. The incidence of the factors or elements shown in Fig. 2 appears as a root cause of the abnormal events analyzed and this figure was used as a weight for Grade 3. If an event history is unavailable, either data from a similar plant is used or Grade 3 is set equal to 1.

2.4. Auditing process quantification

The r_i factors measure the degree of implementation of each element assessed by the plant auditing process. It should be noted that the questionnaire mentioned was applied to all the 12 elements. The criteria to be used are presented in Table 1.

The criteria displayed in Table 1 for the degree of implementation (r_i) was established as follows. Its starting point is a five-point Likert scale (Likert, 1932) developed in Kariuki (2007), ranging from Poor (with $r_i = 0$) to Excellent (with $r_i = 1$). As the auditing process is able to give the degree of implementation, we decided to evaluate the total score and adapt the above Likert scale to the pattern that will be presented later.

Table 1
Definition of scores for the degree of implementation of elements (r_i).

r_i	Ranking	Definition – degree of element implementation
0	Bad	0 < Points[a] < 20%
0.25	Reasonable	20% < Points < 40%
0.5	Average	40% < Points < 60%
0.75	Good	60% < Points < 80%
1	Excellent	80% < Points < 100%

[a] Total points scored by each element in the auditing process (see the third column of Table 5).

The auditing weighting by scoring audited management system items, in order to generate a correction factor for the HEP used in probabilistic safety studies, can become an effective tool in the development and resource allocation process for policy improvements in safety management. The influence of the performance management system on risk or other metrics that might contribute to the decision making processes can also be demonstrated to stakeholders.

In order to correct the original HEP values of existing HRA techniques we propose a quantitative model that is taken from Kariuki (2007) and adapted to our purposes.

Since the goal is to reduce uncertainty to reflect current plant conditions, a mathematical model is proposed to modify the nominal HEP, starting with (Kariuki, 2007):

$$HEP_{mod} = HEP_{UB} \times 10^{\Theta\beta} \tag{1}$$

where

$$\Theta = \log HEP_{LB} - \log HEP_{UB} \tag{2}$$

HEP_{mod} = HEP as modified by the model presented in this work,
HEP_{UB} = upper limit of HEP from THERP or CREAM, and
HEP_{LB} = lower limit of HEP from THERP or CREAM.

and

$$\beta = \sum_{i=1}^{n} w_i r_i \tag{3}$$

where
w_i = Grade 1 × Grade 2 × Grade 3, normalized,
r_i = degree of implementation of the element evaluated by auditing,
Grade 1 = importance weight in relation to the remaining ones,
Grade 2 = influence weight of each factor or element, and
Grade 3 = element weight as root cause or contributor in plant retrospective accident analysis.

Eq. (1) provides an approach that allows to select the most suitable value between lower and upper bound based on values connected to organizational factors. We can assume that for an excellent score for all elements $\beta = 1$ and for a bad score, $\beta = 0$. The β factor is obtained from the assignment of an influence weight (w_i) for each chosen element of the auditing protocol and also from a selected field evaluation of the performance of each plant protocol element (r_i).

Notice that the only difference between our model and Kariuki's is the way we evaluate the β factor since we obtain the weights w_i by using the defined grades and the auditing factors r_i as discussed.

Arguments in favor of the model focused on Eq. (1) are as follows. Models like this have been used in quantified risk assessment for at least 20 years (HSE, 1992) in order to incorporate management and organizational influences. This report discusses the use of scaling methods and the model of Eq. (1) is the most typically used. This discussion goes back to the International Safety

Rating System (ISRS, 1988), and also to Smith and Lines (1990). On the other hand, the American Petroleum Institute discusses the calculation of what is called the management system factor and one may find that the result obtained is quite similar to Eq. (1) (API, 2008, Part II, p. 2–13).

3. Case study

3.1. Introduction

For the application of the proposed model, the accident at the JCO factory of fuel elements in Tokai-Mura, Japan (Furuta et al., 2000) was used.

The accident occurred at a uranium reprocessing plant, where JCO officials shed about 16.6 kg of uranium into a purification tank containing nitric acid, instead of the commonly used 2.4 kg. What followed was a flash of blue light [Cherenkov radiation, Jelley (1958)], due to the criticality of nuclear fuel. Three workers were exposed to high levels of radiation and two of them died.

In the investigation of the accident causes, it has been found that a different procedure from that agreed with the regulatory authorities had been used. According to information, supervisors and possibly managers directed operators to expedite the nuclear fuel processing and workers might have decided to skip more steps than they were ordered to. Additionally, the training provided to employees was insufficient and did not prepare them to deal with the hazards of a possible criticality.

For HEP quantification, the approach by Gertman and Blackman (2002) was taken as a starting point. This approach allows determining the contribution of the elements evaluated in the organization where the event occurred and the modification or adjustment of HEP with the proposed methodology. In a hybrid analysis performed by the authors, three approaches were combined to support the sensitivity analysis of the results reported here. First, a survey of error forcing factors and unsafe acts associated with the event were determined by using ATHEANA. The quantification of operator decision sensitivity analysis and unsafe acts that led to the occurred criticality was based on values contained in THERP and CREAM tables.

The incorporation of organizational factors is carried out by retrospective and prospective analyzes (ATHEANA). In the case of the Tokai-Mura event the role of organizational factors that have caused procedure and licensing basis deviations were analyzed. Six types of unsafe acts were identified and each was quantified. Table 2 presents a series of organizational factors that helped bring about the context surrounding the event. This table was adapted from Gertman and Blackman (2002).

To establish the HEP of four of the six unsafe acts in Table 2, values and confidence limits used to determine the estimates were taken from THERP (Swain and Guttman, 1983) because they are explicitly considered in it. Two of the unsafe acts involved were related to batch or production run design and planning failures of uranium and these tasks, by their descriptions, best fit the values suggested in CREAM (Hollnagel, 1998).

Other accident-related cognitive factors can be listed such as:

- Time pressure to complete the task ignoring safety rules [*Kaizen*, Imai (1986)].
- Lack of deeper technical knowledge in relation to operation safety.
- Poor communication and confusion between the head of the fuel section and the head of the engineering section contributed to the event. It is reasonable to assume that the head of the fuel section had a different thought mechanism: he considered that uranium concentrations that were being used were not different from the design basis.
- Ergonomic contribution, that is, the column layout for material extraction was difficult to access and slowed the process, and the addition point was located 10 cm from the floor. The precipitation tank, on the other hand, was located about 1 m above the ground and it was much easier to use. Cognitive factor: path of least resistance.

Following THERP, a human failure event tree for the Tokai-Mura event was constructed, as shown in Fig. 3 [taken from Gertman and Blackman (2002)]. Following THERP notation, an uppercase letter denotes a HEP and a lowercase letter denotes a success probability.

The initial list of unsafe acts related to organizational factors considered was taken from ATHEANA (see Table 2), as Gertman and Blackman (2002) initially did. However, when the details of the Tokai-Mura were investigated [as Gertman and Blackman (2002) did] it was found that two organizational failures were to be considered, those related to supervisor failure to challenge and correct batching and also supervisor failure to stop batching. In this sense, when the human failure event tree (see Fig. 3) was developed according to the THERP technique, these two organizational failures needed to be considered. This is the reason why the initial 6 unsafe acts turned out to be 8 human failure in the event tree.

The same approach is used in THERP methodology regarding 'Performance Shape Factors', also methodologies like risk-based inspections (API, HSE) use the same approach, the log model is mathematically appropriated to adjust the boundaries of the HEP used even when we multiply the original value to achieve the modified value.

Particularly, the multiplication of probabilities in Table 20 is based on the human reliability event tree considered in THERP, where conditional probabilities can be handled, even when performance shaping factors are considered to make corrections on them. This same issue is considered in ATHEANA and CREAM. For the analysis of the events in the Tokai-Mura accident all events considered are independent.

For each event in the event tree, we pointed out which factors influenced its occurrence and the β factor [Eq. (3)] was obtained to adjust the HEP of each event, called modified HEP. With the application of the model proposed in this paper, the modified HEP was estimated [Eq. (1)]. In order to calculate the β factor [Eq. (3)] for the Tokai-Mura event, w_i and r_i were defined as follows.

Table 2
Identification of unsafe acts by ATHEANA.

	Description of unsafe act	Mechanism
1	Failure to consider the relative mass and geometry in campaign planning	Planning failure
2	Lack of a rigid preplanning condition	Planning failure
3	Failure to select equipment with correct geometry for service execution	Failure of selection during development planning
4	Excess batches on day 1 (4 batches)	Action failure
5	Failure in detecting and correcting the team in preparing batch and equipment using	Loss of opportunity to recover from error
6	Batch excess on day 2 (3 batches). Accumulating more than 6 batches in the equipment	Action failure

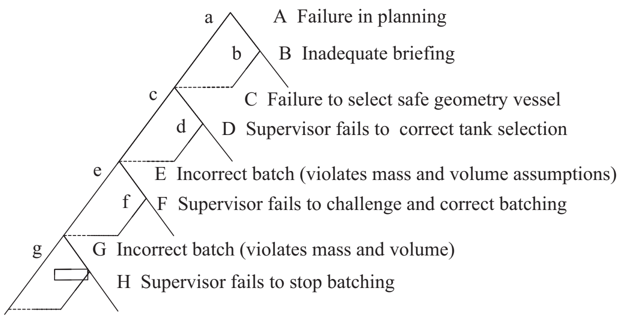

Fig. 3. Tokai-Mura event tree. Gertman and Blackman (2002).

3.2. Grade 1, Grade 2, Grade 3, and r_i case study quantification

This is the starting point for evaluating their weights. For this purpose, it was necessary to formulate proper questionnaires, select experts to respond to them and analyze the results and finally normalize the assigned weights.

The results are displayed in Table 3. It should be mentioned that the influence of each factor over the remaining ones was performed by considering the authors' field experience on process plants and also that only strong influences were taken into account, where a strong influence was set when the influence of an element over another one was found to be equal to or higher than 60%, according to Fernandes (2003). Letter 'F' in Table 3 stands for the word for strong in Portuguese.

For example, it is seen from Table 3 that element # 1 was found to influence elements # 2, # 3 and # 6, that is, Control Center Design influences Remote Operations, Human–Computer Interface, and Environmental Factors, besides itself. As a result, there are 4 influences related to element # 1. This analysis proceeds down to element 12, the number of influences is counted for each element, the total number of influences is obtained and a weight can be obtained. Thus, for example the weight for element # 1 is equal to 4/36 = 0.111.

It is observed that the HEP taken from THERP or CREAM, $HEP_{nominal}$, is modified by the 12 elements displayed in Fig. 2 incorporating performance, cognitive, technological innovation and socio-technical safety management factors. This incorporation is carried out through the relationships between these factors (Grade 1), expert opinion (Grade 2), plant accident history (Grade 3), and an auditing process factor, as will be discussed.

Table 4 presents the element weights obtained from expert opinions to estimate Grade 2. Each average in the twelfth column of Table 4 is the arithmetic mean of the degrees assigned by the experts. As seen, the fourth factor (training) was considered the most relevant (grade equal to 4.7). It should be noted that these weights were attributed by the expert prior to the model application to the Tokai-Mura event (as will be seen, factors 2 and 10 have no influence on the analysis). The ten experts are senior engineers working in the nuclear, chemical and petrochemical industries and Brazilian regulatory bodies.

To measure the degree of implementation of the elements of Fig. 2 a questionnaire was used to assess compliance of each factor. Each verification item is scored from 1 to 5, where 1 means non-compliance and 5 means full compliance. Table 5 summarizes the evaluation of the 12 elements from Fig. 2. The second column of Table 3 displays the number of questions each auditor had to

Table 3
Influence spreadsheet between factors of Fig. 2.

Element	1	2	3	4	5	6	7	8	9	10	11	12	Influence	Grade 1
1		F	F			F							4	0.111
2													1	0.028
3		F											2	0.056
4					F			F		F	F		5	0.139
5								F					2	0.056
6													1	0.028
7				F	F			F					4	0.111
8									F			F	3	0.083
9					F			F					3	0.083
10													1	0.028
11	F			F	F								4	0.111
12				F	F			F	F		F		6	0.167
											Total		36	1.000

Table 4
Element weights in HEP estimation for expert opinions e_i.

Element/expert	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	Average	Grade 2
1	5	2	5	4	4	3	5	3	3	5	3.9	0.081
2	4	2	3	4	4	3	4	3	4	2	3.3	0.068
3	5	3	3	5	5	3	5	4	3	4	4.0	0.083
4	4	5	5	5	5	4	5	4	5	5	4.7	0.097
5	4	2	4	5	5	3	5	5	4	4	4.1	0.085
6	5	1	3	4	5	1	5	4	2	5	3.5	0.072
7	5	4	5	5	5	3	5	5	5	3	4.5	0.093
8	5	5	3	5	4	4	4	4	4	4	4.2	0.087
9	5	5	1	5	5	5	5	3	4	5	4.3	0.089
10	4	4	4	5	4	4	4	4	2	5	4.0	0.083
11	5	5	3	5	4	5	4	3	1	4	3.9	0.081
12	5	5	3	5	5	4	4	2	2	4	3.9	0.081
Total											48.3	

Table 5
Degree of implementation of elements – Incident Investigation.

Element	Number of questions	Total score	%	r_i
1	67	88	31	0.25
2	8	–	–	0.50
3	80	106	39	0.25
4	17	25	29	0.25
5	10	22	44	0.50
6	6	12	40	0.25
7	29	42	35	0.25
8	18	22	24	0.25
9	62	55	33	0.25
10	10	–	–	0.50
11	30	62	41	0.50
12	5	8	32	0.25

Table 6
Degree of implementation of element 12 – Incident Investigation.

Item	Questions	1	2	3	4	5	Comments
12.1	Are criteria for information on accidents or incidents defined?		X				Non uniform
12.2	Are accidents or incidents immediately investigated?	X					
12.3	Are accident or incident investigators properly trained?	X					
12.4	Do accident or incident investigations point out their root causes (management system failure)?		X				
12.5	Are corrective actions implemented with accompanying action plans?		X				No monitoring
	Total points = 8 (32%) (r_i = 0.25)						

Table 7
Weighting of elements in accident history (Note Grade 3).

Element	Influence	Grade 3
1	37	0.193
2	4	0.021
3	3	0.016
4	27	0.141
5	13	0.068
6	12	0.063
7	7	0.036
8	5	0.026
9	29	0.151
10	29	0.151
11	22	0.115
12	4	0.021
Total	192	1

answer. The third column displays the total score each expert has assigned, while the fourth column exhibits the percentage of the maximum score for each element [by considering that this maximum score is equal to the maximum grade (5) multiplied by the number of questions]. To set the r_i, the questionnaire adapted from CCPS (2007) was completed, as defined in the presented model, based on information available in Furuta et al. (2000). No scoring for elements 2 and 10 were considered because they did not apply to the Tokai-Mura plant. Modifications and grouping of elements in the original CCPS questionnaire have been made to simplify the scoring and model application. As an example, Table 6 displays the degree of implementation for element 12 (accident investigation), as evaluated by the expert panel. The total points (in %) is obtained by summing up the scores attributed to the different items. Items 12.1, 12.4 and 12.5 have been given score 2, while items 12.3 and 12.4 have been given score 1, so that the total score is 8. On the other hand, the maximum possible score is 25 (when all items are given score 5). In this sense, an 8/25 = 32% percentage score is obtained, as can be seen from Table 6. It is important to stress that the degrees of implementation displayed on the last column of Table 5 are used throughout the analysis and the results were obtained by performing the same calculations displayed in Table 6 for element # 12 (incident investigation) and by using the criteria displayed in Table 1. As will be seen, they are reproduced in forthcoming tables (as, for example, Table 8) for convenience.

Table 8
Element weights (w_i) for the Tokai-Mura plant analysis.

Element	Grade 1	Grade 2	Grade 3	w_i	$w_{i,n}$[a] (%)	r_i	$w_{i,n} \cdot r_i$
1	0.111	0.081	0.193	0.001729	23.0	0.25	0.05741
3	0.028	0.068	0.021	0.000072	1.0	0.25	0.00238
4	0.056	0.083	0.016	0.001901	25.2	0.25	0.06311
5	0.139	0.097	0.141	0.000319	4.2	0.50	0.02120
6	0.056	0.085	0.068	0.000126	1.7	0.50	0.00835
7	0.028	0.072	0.063	0.000377	5.0	0.25	0.01253
8	0.111	0.093	0.036	0.000189	2.5	0.25	0.00627
9	0.083	0.087	0.026	0.001121	14.9	0.25	0.03721
11	0.083	0.089	0.151	0.001028	13.7	0.50	0.06827
12	0.028	0.083	0.151	0.000280	3.7	0.25	0.00931
$\sum w_i$				0.007530			

[a] Normalized w_i.

Referring to the discussion just after Fig. 1, take, for instance, the first question from Table 6. The purpose of this question is to show whether the plant has a clear criterion to learn from incidents or accidents.

In the absence of data from the JCO Tokai-Mura plant, a retrospective analysis of unusual occurrence in process plants in the last three years (ABIQUIM, 2010) was used to estimate Grade 3. A set of experts was asked to analyze the events and identify what elements from Fig. 2 influenced each event. The second column of Table 7 presents the number of events influenced by each element and the third column displays the normalized weights of elements from the mentioned accident history. For example, $w_1 = 37/192 = 0.193$. In many cases, more than one element influences a given event in the data set.

3.3. Element weight quantification for the Tokai-Mura case study

The w_i, composed of Grade 1 (Table 5) and Grade 2 (Table 2) and Grade 3 (Table 7), are displayed in Table 8. The non-normalized weighted factor w_i is equal to the product of grades 1, 2, and 3 for that factor. Thus, for example, $w_1 = 0.111 \times 0.081 \times 0.193 = 0.001729$.

3.4. Application of element weights to events in the human event tree

As mentioned earlier, for each event in the event tree we pointed out which factors influence its occurrence and the β factor for each event was obtained to adjust the HEP. Table 9 displays the nominal HEP data for each event in the tree shown in Fig. 3.

For each human error event of Fig. 3 the applicable elements of Fig. 2 were identified and summarized in Table 10.

Tables 11–18 display details on the β factor calculation for all events $(A, \ldots, H)$ of Fig. 3.

In Table 11 the first column presents the applicable elements for event A taken from the event tree of Fig. 3. The second column repeats the applicable weighting factors calculated in Table 8. For simplicity, we normalized these weighting factors, as presented in the third column. The degree of implementation, as obtained in Table 5, is reproduced in the fourth column of this table. The last

Table 9
HEP values based on estimates of CREAM and THERP.

Item	Failure description (unsafe act)	LB[a]	$HEP_{nominal}$	UB[b]	Ref.
A	Failure of correct directing and/or consideration of mass, volume and geometry in the safe preparation of batch (P2 inadequate planning)	0.001	0.01	0.1	CREAM[c], Tab. 9
B	Failure to conduct a thorough briefing in batch preparation (I2 – decision error with P2 – planning error)	0.001	0.01	0.1	CREAM, Tab. 9
C	Failure to select the device geometry (select the precipitation tank instead of the extraction column)	0.0034	0.01(3[e])	0.0294	THERP[d], Tab. 20-13. Item 1
D	Supervisor fails to fix selected tank	0.048	0.2 (5[e])	0.55	THERP, Tab. 20-22. Item 2
E	Accumulation of 4 batches in the precipitation tank on day 1	0.002	0.01(5[e])	0.048	THERP, Tab. 20-6. Item 1
F	Failure of the supervisor and the production head to detect and correct the operator group decision on the tank mode use and number of batches	0.048	0.2 (5[e])	0.55	THERP, Tab. 20-22. Item 2
G	Incorrect introduction of 3 additional batches in the precipitation tank on day 2	0.002	0.01(5[e])	0.048	THERP, Tab. 20-6. Item 1
H	Supervisor fails to stop production	0.048	0.2 (5[e])	0.55	THERP, Tab. 20-22. Item 2

[a] Upper Bound.
[b] Lower Bound.
[c] Hollnagel (1998).
[d] Swain and Guttman (1983).
[e] THERP's error factor (EF).

Table 10
Relationship between the events of human event trees (Fig. 4) and applicable elements of Fig. 2.

Human failure event (Fig. 4)	Applicable elements (Fig. 2)
A	1, 3, 4, 5, 7, 8, 9, 11
B	4, 5, 7, 8, 9
C	4, 8, 9, 11
D	4, 5, 7, 8, 11, 12
E	4, 5, 7, 8, 9, 12
F	4, 5, 7, 8, 11
G	4, 5, 7, 8, 9, 12
H	4, 5, 7, 8, 11, 12

Table 11
β factor for event A of the human event tree (Fig. 3).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	w_ir_i
1	0.001729	0.256693	0.25	0.064173
3	0.000072	0.010673	0.25	0.002668
4	0.001901	0.282176	0.25	0.070544
5	0.000319	0.047407	0.50	0.023704
7	0.000377	0.056035	0.25	0.014009
8	0.000189	0.028017	0.25	0.007004
9	0.001121	0.166370	0.25	0.041593
11	0.001028	0.152628	0.50	0.076314
Sum	0.006735	1	β =	0.300009

column of Table 5 displays the calculation of the product between the normalized weighting factor and the degree of implementation factor for each element. Thus, for example, $w_{1,normalized} \times r_1 = 0.256693 \times 0.25 = 0.064173$. Note that the β factor is the sum of all $w_{i,normalized} \times r_i$ and is equal to 0.300009 for the case of event A. This same reasoning applies to events B–H in Tables 12–18.

Table 19 presents the details for the calculation of the modified human error probabilities by considering Eq. (1). Note that the β values calculated in Tables 11–18 were reproduced in Table 19 for easiness of understanding. Thus, for example, by using Eq. (2) for failure event A, $\Theta = \log\ 0.0001 - \log\ 0.01 = -2$ and, from Eq. (1), $HEP_{mod} = 0.1 \times 10^{(-2)(0.300009)} = 0.0251$.

We can observe from the adjusting factor of the proposed model that if $\beta = 0$ (bad plants), $HEP_{mod} = HEP_{UB} * 10^{*0} = HEP_{UB}$ and if $\beta = 1$ (good plants), $HEP_{mod} = HEP_{UB} * 10^{*1} = HEP_{UB} * 10^{\mathrm{Log}(HEP_{LB}/HEP_{UB})} = HEP_{LB}$.

Table 12
β factor for event B of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	w_ir_i
4	0.001901	0.486505	0.25	0.121626
5	0.000319	0.081736	0.50	0.040868
7	0.000377	0.096611	0.25	0.024153
8	0.000189	0.048305	0.25	0.012076
9	0.001121	0.286843	0.25	0.071711
Sum	0.003907	1	β =	0.270434

Table 13
β factor for event C of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	w_ir_i
4	0.001303	0.359337	0.25	0.089834
8	0.000162	0.044599	0.25	0.011150
9	0.001281	0.353108	0.25	0.088277
11	0.000881	0.242956	0.50	0.121478
Sum	0.003627	1	β =	0.310739

Table 14
β factor for event D of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	w_ir_i
4	0.001901	0.464189	0.25	0.116047
5	0.000319	0.077987	0.50	0.038993
7	0.000377	0.092179	0.25	0.023045
8	0.000189	0.046090	0.25	0.011522
11	0.001028	0.251079	0.50	0.125540
12	0.000280	0.068476	0.25	0.017119
Sum	0.004094	1	β =	0.332266

Table 15
β factor for event E of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	w_ir_i
4	0.001729	0.430586	0.25	0.107646
5	0.000319	0.079523	0.50	0.039761
7	0.000377	0.093995	0.25	0.023499
8	0.000189	0.046997	0.25	0.011749
9	0.001121	0.279075	0.50	0.069769
12	0.000280	0.069825	0.25	0.017456
Sum	0.004015	1	β =	0.269881

Table 16
β factor for event *F* of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	$w_i r_i$
4	0.001901	0.498311	0.25	0.124578
5	0.000319	0.083719	0.50	0.04186
7	0.000377	0.098955	0.25	0.024739
8	0.000189	0.049478	0.25	0.012369
11	0.001028	0.269536	0.50	0.134768
Sum	0.003814	1	β =	0.338314

Table 17
β factor for event *G* of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	$w_i r_i$
4	0.001901	0.453928	0.25	0.113482
5	0.000319	0.076263	0.50	0.038131
7	0.000377	0.090142	0.25	0.022535
8	0.000189	0.045071	0.25	0.011268
9	0.001121	0.267635	0.25	0.066909
12	0.000280	0.066962	0.25	0.016741
Sum	0.004187	1	β =	0.269066

Table 18
β factor for event *H* of the human event tree (Fig. 4).

Applicable elements (Fig. 2)	Weights	Normalized weights	r_i	$w_i r_i$
4	0.001901	0.464189	0.25	0.116047
5	0.000319	0.077987	0.50	0.038993
7	0.000377	0.092179	0.25	0.023045
8	0.000189	0.046090	0.25	0.011522
11	0.001028	0.251079	0.50	0.12554
12	0.000280	0.068476	0.25	0.017119
Sum	0.004094	1	β =	0.332266

Table 19
Calculation of the Θ factor [(Eq. (1)] and of the modified Human Error Probabilities.

Human failure event (Fig. 4)	Θ	β	HEP_{mod}
A	−2	0.300009	0.0251
B	−2	0.270434	0.0288
C	−0.9542	0.310739	0.0152
D	−1.3979	0.332266	0.3432
E	−1.3979	0.269881	0.0210
F	−1.3979	0.338314	0.3366
G	−1.3979	0.269066	0.0210
H	−2.3979	0.332266	0.1597

Let us now consider the modified HEPs as shown on the last column of Table 19 and compare these modified HEPs with the lower HEP bounds on the third column of Table 9. It can be inferred that all modified HEPs fall within the interval defined by the lower and upper bounds shown therein. The modified HEPs for the Tokai-Mura case study clearly show the model adherence to the plant situation because the plant practice was inadequate.

Table 20 presents the results of calculating the nominal and the modified HEPs, by using the β factor for each tree branch of the event tree displayed in Fig. 3.

Let us discuss, for example, the calculation of the *AbCD* event tree branch. It is important to mention that the notation for each sequence is based on the THERP notation, that is, an upper case letter means a failure and a lower case letter means a success. For the chosen tree branch, events *A*, *C*, and *D* represent failures, and event *b* represents a success. The upper bounds for the unsafe act HEPs in this tree branch are taken from Table 9. Thus, the nominal HEP for this tree branch is obtained as follows: $0.01 \times (1 - 0.01) \times 0.01 \times 0.2 = 1.98 \times 10^{-5}$. On the other hand, the modified HEP for this tree branch is given by (note that the unsafe act HEPs are now taken from Table 19) is obtained from $0.0251 \times (1 - 0.0288) \times 0.0152 \times 0.3422 = 1.27 \times 10^{-4}$.

Table 20
Calculation of the final modified HEP for the Tokai-Mura accident (HEP_{UB} values).

Tree branch	Nominal HEP	Modified HEP
AB	1.00E−04	7.23E−04
AbCD	1.98E−05	1.27E−04
aCD	1.98E−03	5.07E−03
acEF	1.96E−03	6.78E−03
AbCdEF	1.58E−07	1.71E−06
aCdEF	1.58E−05	6.85E−05
acEfGH	1.57E−05	4.49E−05
aceGH	3.26E−03	3.16E−03
AbcEF	1.96E−05	1.70E−04
AbceGH	1.94E−05	7.90E−05
AbCdeGH	1.57E−07	7.99E−07
AbCdEfGH	1.27E−09	1.14E−08
Total	7.39E−03	1.62E−02

For the case of the Tokai-Mura accident the higher values of the confidence intervals (HEP_{UB}) from THERP and CREAM were used, as suggested in the techniques themselves, due to organizational deficiencies and plant layout. It was found that the final value of the Tokai-Mura event, HEP_{mod}, by using the model proposed in this paper, is 2 times the nominal HEP. Taking into account that the events are not depended this result shows that the consideration of organizational factors provides a more realistic view of plant behavior in the face of abnormal events, and also that the involved human failure probabilities are much higher. This result highlights the fact that when performing probabilistic safety assessments of nuclear facilities, accidental scenarios can present more pessimistic (conservative) results.

4. Conclusions and recommendations

It has become clear at safety conferences and congresses in the nuclear and chemical and petrochemical process fields that existing laws and regulations, especially some requirements of international regulatory bodies such as the CSB (Chemical Safety Board, USA), are more and more explicit in regarding the implementation of human reliability analysis (HRA) as a way of risk reduction. However, most organizations still do not have efficient mechanisms to understand and implement policies for human factors analyses. This work offers a contribution to include in a comprehensive manner the elements that influence human error.

A contribution of the proposed model is to allow seeing how elements relate and how they influence HEP quantification, which allows directing efforts in the short and long run to reduce HEPs or even review the effectiveness of the efforts being made to reduce them.

From the point of view of in-plant safety management, we can also graphically see, as shown in the radar chart of Fig. 4, a way to use the quantitative results of the analysis performed in this paper in order to improve human reliability.

The radar chart shows the role of the elements listed in Fig. 2 in the analysis developed for the Tokai-Mura event. For each element *i* its w_i factor (recall that this factor takes into account the influence of grades 1, 2, and 3) as evaluated in Table 8 is used together with the auditing factor r_i (obtained from Tables 5 and 6) to give the individual joint influence factors $w_i r_i$. This figure is used to display the elements in Fig. 4 and a color[1] criterion was inserted

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

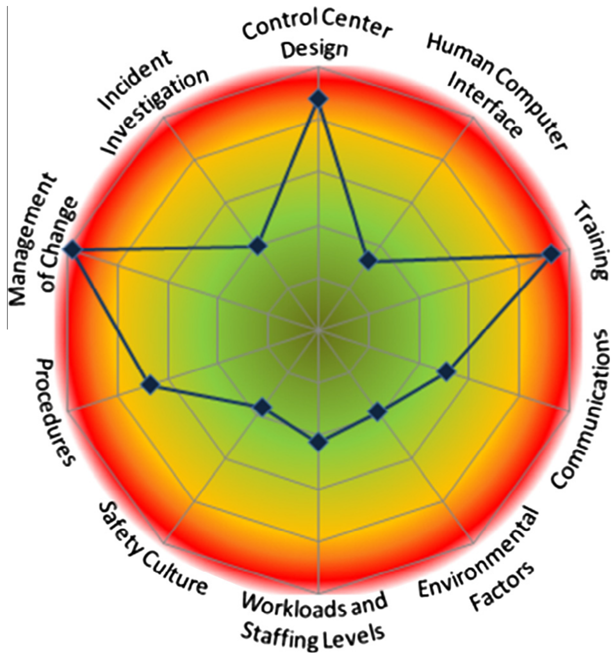

Fig. 4. Radar chart of the relative influence of elements in HEP estimation (Fig. 2).

for illustrative purposes. In this sense, the elements that most contribute to human failure are in the red region. So, for example, Control Center Design (element # 1), Training (element # 4), and Management of Change (element # 11) are the three most relevant for the Tokai-Mura plant. Notice that the HEPs used in the quantification analysis were not used here because the intent is to use solely those factors that might influence the basic HEPs, and not the HEPs themselves. This radar chart can be considered as a useful tool to assist in directing resources and efforts to improve plant safety.

It is interesting to notice that if the $w_i r_i$ factors calculated in Tables 11–18 were used instead of those displayed in Table 7 the same conclusion would be drawn, in general. For example, from Table 8 one can see that the most relevant elements are the same (1, 4, and 11). The use of the data in Tables 11–18 implies that one is considering the relevant failure events for the human failure probability analysis and the $w_i r_i$ are normalized accordingly. As can be seen from these tables, element # 4 is one of the most relevant for all failure events, element # 9 (Procedures) is to be considered for failure events *B*, *C*, *E*, and *G*, and element # 8 (Safety culture) appears as relevant for failure events *B* and *F*.

The proposed audit questionnaire should be specialized and validated through field tests.

We also recommend a further research on the use of archetypes of system dynamics as shown by Marais et al. (2007) for a better evaluation of Grade 3.

The use of archetypes might be important for evaluating grade 3 because by analyzing the events in the event data bank one could find new perspectives that would result in completely different and more realistic figures in the second column of Table 6.

There are many important social system aspects of a strong safety culture, like informal organizational structures and social interaction processes, including leadership, negotiation, problem solving, decision-making, and partnership. Problem solving after incidents and operational anomalies is an important component of safety culture, particularly as it relates to identifying and eliminating root causes rather than merely the symptoms of deeper problems. Due to this we also recommend a further research on the use of archetypes of system dynamics as shown by Marais et al. (2007) for a better evaluation of Grade 3.

The use of archetypes might be important for evaluating grade 3 because by analyzing the events in the event data bank one could find new perspectives that would result in completely different and more realistic figures on the second column of Table 7 and also Table 20, considering that the events used to calculate the final HEP are not dependent.

Marais et al. (2007) developed two groups of safety archetypes, one for dealing with the challenges of maintaining safety and the other for facing side effects and symptomatic responses. As examples of safety archetypes of the first group one can mention 'Stagnant safety practices in the face of technological advances' and 'Decreasing safety consciousness' and as examples of the second group one has 'Fixing symptoms rather than root causes' and 'The vicious cycle of bureaucracy'.

The use of archetypes allows one to incorporate nonlinear elements that are known to influence unusual occurrences in process plants. Consideration of the influence of nonlinear factors will increase the accuracy of HEP estimation. This additional aggregated factor might indicate that a system stabilizes under the safety function (that is, no occurrence of incidents or accidents). This stabilization induces a delay in the perception of the safety function at the plant, which is brought to a natural relaxation due to the comfortable situation of absence of abnormal events induced by human error.

The analysis performed in this paper has shown that consideration of organizational features by expert opinion elicitation and auditing may unveil relevant plant shortcomings whose analysis should be deepened. Periodical reevaluation by means of a radar diagram, for example, might be of use to show how managerial decisions have contributed to improve plant safety.

References

ABIQUIM, 2010. Responsible Care Program. In: Process Safety Committee Meeting Notes. Brazilian Association of Chemical Industries, São Paulo, SP, Brazil.

Alvarenga, M.A.B., Frutuoso e Melo, P.F., Fonseca, R.A., 2014. A critical review of methods and models for evaluating organizational factors in human reliability analysis. Prog. Nucl. Energy 75, 25–41.

API, 2008. Risk-based Inspection Technology. American Petroleum Institute, Washington, DC, US.

Ayyub, B.M., 2001. Elicitation of Expert Opinions for Uncertainty and Risks. CRC Press, Boca Ratton, FL.

Bieder, C., Le-Bot, P., Desmares, E., Bonnet, J.-L., Cara, F., 1998. MERMOS: EDF's new advanced HRA method. In: Mosleh, A., Bari, R.A. (Eds.), Probabilistic Safety Assessment and Management (PSAM 4). Springer-Verlag, New York.

CCPS, 2000. Guidelines for Chemical Process Quantitative Risk Analysis. Center for Chemical Process Safety, American Institute of Chemical Engineers, Wiley, New York, NY.

CCPS, 2001. Layer of Protection Analysis: Simplified Process Risk Assessment. Center for Chemical Process Safety, American Institute of Chemical Engineers, Wiley, New York, NY.

CCPS, 2007. Human Factors Methods for improving Performance in the Process Industries. Center for Chemical Process Safety, American Institute of Chemical Engineers, Wiley, New York, NY.

Fernandes, A.C., 2003. Dynamic Scorecard: Towards integrating System Dynamics and the Balanced Scorecard D.Sc. Dissertation. COPPE/UFRJ, Rio de Janeiro, RJ, Brazil (in Portuguese).

Fonseca, R.A., Alvim, A.C.M., Alvarenga, M.A.B., Frutuoso e Melo, P.F., 2013. A THERP/ATHEANA analysis of the latent operator error in leaving EFW valves closed in the TMI-2 accident. Sci. Technol. Nucl. Install. http://dx.doi.org/10.1155/2013/787196.

Furuta, K., Sasou, K., Kubota, R., Ujita, H., Shuto, Y., Yagi, E., 2000. Human factor analysis of JCO criticality accident. Cogn. Technol. Work 2, 230–231.

Gertman, D.I., Blackman, H.S., 2002. Sensitivity analysis case study: incorporating organizational factors in HRA. In: Proceedings of the International Workshop Building the New HRA: Errors of Commission from Research to Application. NEA/CSNI/R(2002)3. Nuclear Energy Agency, Issy-les-Moulineaux, France, pp. 195–207.

Hollnagel, E., 1998. Cognitive Reliability and Error Analysis Method (CREAM). Elsevier, Oxford, UK.

Hollnagel, E., 2004. Barriers and Accident Prevention. Ashgate, Hampshire, UK.

HSE, 1992. The Development of a Model to Incorporate Management and Organisational Influences in Quantified Risk Assessment, HSE Contract Research Report No. 38/1992. Health and Safety Executive, London.

IAEA, 2007. IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection. International Atomic Energy Agency, Vienna, Austria.

Imai, M., 1986. Kaizen: The Key to Japan's Competitive Success. Random House, New York, US.
ISRS, 1988. International Safety Rating System. International Loss Control Institute, Atlanta, Georgia, US.
Jelley, J.V., 1958. Cerenkov Radiation and its Applications. Pergamon Press, London, UK.
Kariuki, S.G., 2007. Integrating Human Factors into Chemical Process Quantitative Risk Analysis Ph.D. Dissertation. Berlin Technical University, Berlin, Germany.
Likert, R., 1932. A technique for the measurement of attitudes. Arch. Psychol. 140, 1–55.
Marais, K., Saleh, J.H., Leveson, N.G., 2007. Archetypes for organizational safety. Saf. Sci. 44, 565–582.
NRC, 2000. Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA). NUREG 1624, US Nuclear Regulatory Commission, Washington, DC.
NRC, 2005. Good Practices for Implementing Human Reliability Analysis. U. S. Nuclear Regulatory Commission, NUREG-1792, Washington, DC.
NRC, 2006. Evaluation of Human Reliability Analysis Methods against Good Practices. U. S. Nuclear Regulatory Commission, NUREG-1842, Washington, DC.
OGP, 2005. Human Factors, International Association of Oil and Gas Producers, London Available at <info.ogp.org.uk/hf/> (accessed May 2015).
Papazoglou, I.A., Bellmay, L.J., Hale, A.R., Aneziris, O.N., Ale, B.J.M., Post, J.G., Oh, J.I.H., 2003. I-Risk: development of an integrated technical and management risk methodology for chemical installations. J. Loss Prev. Process Ind. 16, 575–591.
Saaty, T.L., 2000. Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process. RWS Publications, Pittsburgh, PA.
Sirrett, P., 2013. Could HRA have Prevented the Buncefield Disaster?, TCE Today, September, pp. 39–40.
Smith, A.J., Lines, I.G., 1990. Analysis of the Results of the Paired Comparison Test on Management and Organizational Influences for Use in Quantified Risk Assessment. WS Atkins Report M1387.001, Issue 2, August.
Sousa, A.L., Ribeiro, A.C., Brasil, F.S., 2007. How to incorporate the health, safety and environment management system in quantitative risk assessments. In: Proceedings of CCPS 22nd Annual International Conference. Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY.
Swain, A.D., Guttman, H.E., 1983. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, NUREG/CR-1278. US Nuclear Regulatory Commission, Washington, DC.