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Chapter 6

# An Experimental Study on Developing a Cognitive Model for Human Reliability Analysis

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Additional information is available at the end of the chapter

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**Abstract**

Serious incidents that occur inside or caused by industrial plants represent a very critical issue. In this context, the human reliability analysis (HRA) is an important tool to assess human factors that influence human behaviour in disasters scenario. In fact, the reliability assessment of interaction between human-machine systems is an important factor that affects the overall performance and safety in industrial plants. However, even though HRA techniques have been available for decades, there is not a universal method/procedure to reduce human errors that affect human performance. This study aims to design a novel approach to investigate the relationship between human reliability and operator performance considering the dependence on the available time to make decisions.

**Keywords:** disaster management, human reliability analysis, cognitive model, PSFs

## 1. Introduction

The increasing complexity of industrial systems requires the adoption of adequate approaches to manage emergency situations in case of accidents and disasters. In this context, the analysis of human reliability represents a crucial task [1]. In fact, the human factor is a predominant element in the study of accidents/disasters, not only in probability level, but also in terms of severity of the expected effects [2]. HRA is a set of techniques which describes the conditions of the operator during the work, taking into account errors and unsafe actions [3]. In other words, HRA aims to describe the physical and environmental conditions in which operators shall carry out their tasks, considering errors, skills, experience and ability [4]. The importance of the topic is the reason as we conducted a research on Scopus database, the largest abstract and citation database of peer-reviewed literature. Search string used in the literature survey was

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'*human reliability analysis*'. String was defined according to the standards of Scopus database. Only articles in which the string '*human reliability analysis*' was found in key words were analysed. The analysis on Scopus pointed out that from 1964 (first year in which the first article appeared) until February 2017 (period of survey) a set of 40,958 documents have been published divided in 32,865 articles, 3671 conference papers and the remaining part on books, editorials, letters, etc. Result showed that the scientific production on this topic is very wide and covers many scientific areas (engineering, medicine, social science, etc.). Furthermore, it is interesting to note that most of the publications (13,842) have been published in the USA. Of course, since the research was very general, it is evident that the large amount of documents found does not allow to have a specific analysis regarding our specific scientific interest. Thus, considering our specific field of interest, we refined our search applying a preliminary filter. Search string used was '*human reliability analysis AND industrial plant*'. Only articles in which the string '*human reliability analysis AND industrial plant*' was found in key words were analysed. In this case, only 46 documents were found from 1984 to 2017. It means that on average two articles per year have been published. Similarly, we conducted a deeper analysis applying a second filter. Search string used was '*human reliability analysis AND industrial plant AND cognitive model*''. Firstly, considering the three criteria: (1) article title, (2) abstract and (3) key words), only six articles were found. While taking into account the criterion 'keywords', only four articles were found.

Among the documents found, we selected some of them. An interesting point of view is analysed by Massaiu [5]. In his paper, a new approach is proposed to address the weaknesses of the HRA method or in other words the lack of empirical support of HRA method. In detail, a test of the ability to identify regularities among environmental conditions (procedures), crew expertise (teamwork) and crew behaviours were investigated. Liu et al. [6] apply the cognitive reliability and error analysis method (CREAM) to calculate the failure probability of human cognitive activities for mine hoisting operation. Cheng and Hwang [7] outline the human error identification (HEI) techniques that currently exist to assess latent human errors on the chemical cylinder change task.

Literature review shows that the human reliability analysis is an issue of growing importance in the scientific world. But, there are some limits. The major limit of HRA is related to the uncertainty which does not allow full use of the reliability analysis [8]. Furthermore, several human reliability models follow a static approach, in which human errors are described as omission/commission errors [9]. Really, in our opinion, it is essential to consider the physical and cognitive environment depending on the time in which human errors develop. This consideration led us to the development of an integrated reliability model which takes into account the dynamic influence of operators. Thus, our study aims to propose a novel approach to investigate the relationship between performance shaping factors (PSFs) and operator performances. In HRA, PSFs encompassed the various factors that affect human performance. PSFs can increase or decrease the probability of human error [10, 11]. Our research aims to develop a multi-dimensional and structural model in order to apply it in different types of activities and in different disaster scenarios to avoid potential operational errors. The model takes into account technical and environmental factors that can influence the decisions and the actions of operators. The model combines the cognitive aspects of operational analysis, the

mathematical approach and the probabilistic quantification of the error. A real case study concerning the adoption of best practices for a petrochemical plant's control room during an emergency situation is presented. The rest of the chapter is organized as follows: in Section 2, experimental design is analysed; in Section 3, a detailed model in a real case study is presented; in this section the main results of the model are discussed and finally, in Section 4, conclusion and future development are summarized.

## 2. Experimental study: the model framework

The most influential models of operator behaviour [12, 13] assume three levels of behavioural errors: (1) automatic reactions demanding little or no attention; (2) attentive reactions when one knows how to handle in a certain, well-known situation; and (3) creative, analytical reactions when confronted with new, unknown problems without off-the-shelf solutions. The above classification is certainly helpful, but it is not sufficient to take into account the dynamism that characterized human-machine systems reliability. It is necessary to reduce human error and

| Step | Procedure | Description | Observations |
|---|---|---|---|
| 1 | Preliminary analysis | **Preliminary Scenario Analysis** | It analyzes the reference scenario by choosing the activities of the decision maker |
| 2 | GTTs assessment | **Generic task assessment** | Each activity can be associated with a generic task that represents its |
| 3 | ∀ GTT f (Weibull) | **Weibull function definition** | Weibull function parameters calculationfor each GTTs |
| 4 | PSFs choiche | **PSFs choiche** | It chooses the PSFS that best influence the decision or actions carried out by the decision maker |
| 5 | PSF comp | **Index $PSF_{comp}$ determination** | It defines multipliers than the "SPAR-H method". It calculates the indexe $PSF_{comp}$ |
| 6 | HEP cont | **Index $HEP_{cont}$ determination** | Determination of the $HEP_{cont}$ depending from the GTTs and PSFs |
| 7 | HEP cont *w/d* | **Index $HEP_{cont\ w/d}$ determination** | Determination of the $HEP_{cont}$ depending from the GTTs and PSFs and considering the relation of the PSFs |
| 8 | post 8° hour of work | **HEPnom post 8° hour of work determination** | Determination of the $HEP_{cont}$ depending from the GTTs and PSFs and considering the relation of the PSFs |
| 9 | HEP tot | **HEPtot determination**<br>**Results Analysis and discussion** | It is replacing the $HEP_{cont}$ with the $HEP_{tot}$ |

**Figure 1.** Methodological flowchart (author's elaboration).

hence to develop the capability to find (intuitively) solutions to unexpected problems. Our model is based on the above consideration. In detail, the model framework consists in nine different steps (as shown in **Figure 1**): Step 1—Preliminary analysis; Step 2—Generic tasks assessment (GTTs); Step 3—Definition of the Weibull distribution function; Step 4—Choice of performance shaping factors (PSFs); Step 5—Determination $PSF_{comp}$; Step 6—Determination $HEP_{cont}$; Step 7—Determination $HEP_{cont\ w/d}$; Step 8—Rating $HEP_{nom}$ after the 8th hour of work and Step 9—Determination $HEP_{tot}$.

The model is applied in a real case study concerning the emergency management within a petrochemical company. In detail, the model aims to investigate the adoption of best practices for company's control room in order to ensure a consistent response under demanding circumstances.

## 3. Model development: description of a real case study

In the present section, a detailed analysis of each step is provided.

### 3.1. Step 1: preliminary analysis

The first step aims to define actions carried out by operators. At each operations is assigned a human error probability ($HEP_{nom}$), that represents the unreliability of the operator and it represents a critical point to perform a proper human reliability analysis [14]. Obviously, the probability of error is a function of the time. Therefore, increasing the working hours, it means that the likelihood of error increases. Scenario analysed concerns the management of a fire occurred in the petrochemical plant. The key element is about maintaining a state of readiness and having an awareness of the working environment. **Figure 2** shows the industrial plant under the study and the control room.

During a fire emergency, it is important to set common standards and to ensure that personnel are continuously trained, assessed and re-assessed against these summaries of best practice. All fire alarms are to be taken seriously. Evacuation of the facility is mandatory until the signal to re-enter has been given by appropriate personnel and the alarm bells have ceased ringing. **Figure 3** shows procedures that are to be followed any time a fire alarm sounds.

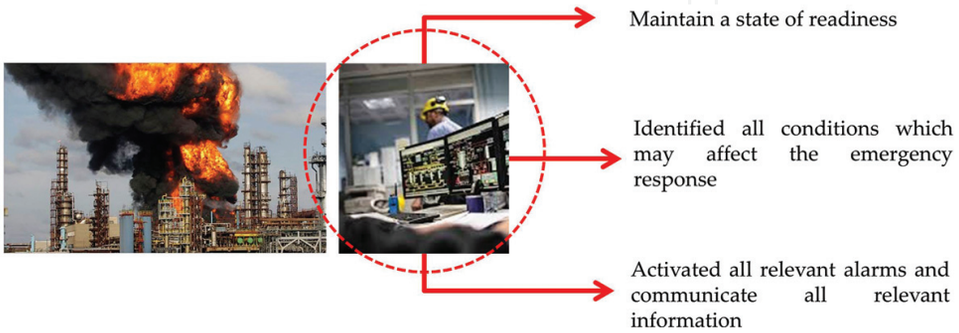


**Figure 2.** Scenario under study.

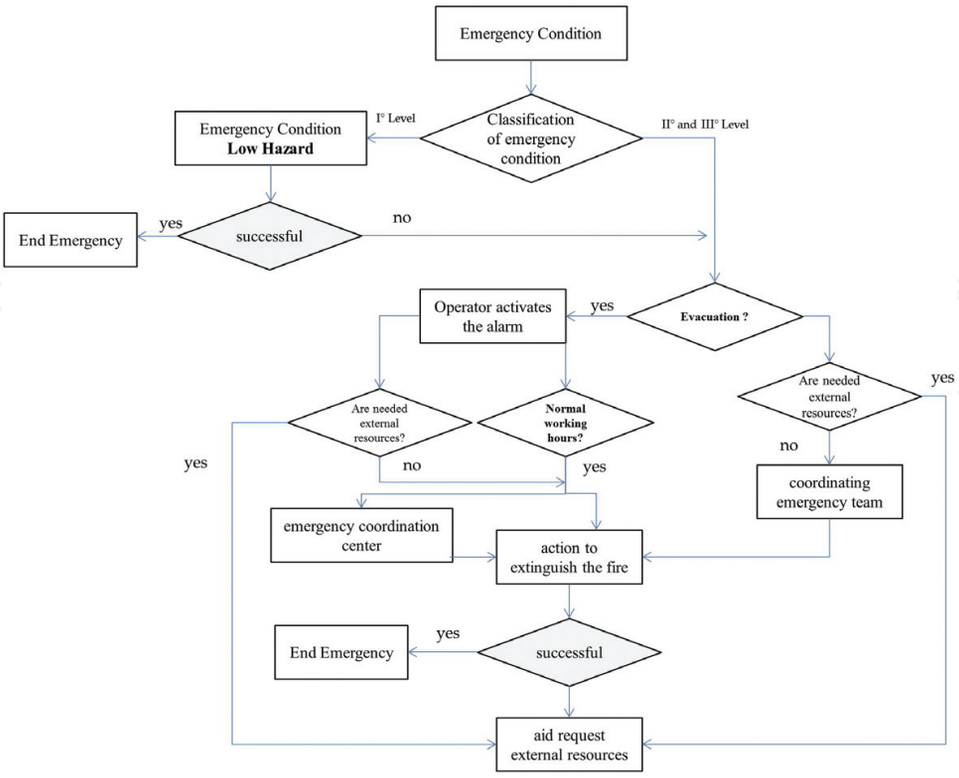


**Figure 3.** Fire emergency protocol.

In detail, two operators were engaged in the control room, but only one was in charge of handling emergency procedures during the fire. Operator was responsible to activate emergency procedure that includes (1) Total block of the furnaces; (2) Close all turbines; (3) Propane valve closing; (4) Locking the sequence handling propane; (5) Flow control valves closing and (6) Closure of the emergency procedure. The three main emergency conditions that may be occurred are (1) Low hazard occurring despite the emergency the decision maker has been monitoring the situation; (2) Moderate hazard to occur the decision maker emergency can take wrong decisions; and (3) High hazard, the decision maker can make a mistake with a good chance.

### 3.2. Step 2: generic tasks assessment (GTTs)

The present step aims to define generic tasks (GTTs) or a set of generic error probabilities for different type of tasks. The tasks were defined according the scientific literature [15]. Literature proposes for each task of human unreliability a set of values defined than the 5th percentile (for the first hour of work) and at the 95th percentile (for the eighth hour of work). The reliability is maximum at the first hour of work ($t$ = 1) and minimum at the eighth work time ($t$ = 8), as defined in Eq. (1):

$$k = 1 - HEP_{nom}(t) \forall t \in [1; 8] \tag{1}$$

$k$ parameter represents the value of the operator's reliability.

In our case study, only three significant generic tasks (4, 7 and 8) were considered in order to approximate operator's activities in the control room, as shown in **Table 1**.

### 3.3. Step 3: definition of the Weibull distribution function

After defining GTTs, the probability of error associated with each GTTs were defined, according to Weibull probability distribution that best describes the probability of error. In detail, the probability of error is described by the index Human Error Probability (HEP), defined according to the Weibull distribution, as follows (Eq. (2)):

$$HEP_{\text{nom}} = 1 - e^{-\alpha t^{\beta}} \tag{2}$$

where the parameters $\alpha$ and $\beta$ represent respectively the scale and the shape of the curves. The above formula assumes the minimum value of reliability during the first hour of work and a maximum value at the eighth hour of work. Consequently, the probability distribution of error Eq. (2) is adapted as follows (Eq. (3)):

$$\begin{cases} HEP_{\text{nom}}(t) = 1 - k * e^{-\alpha(1\ -t)^{\beta}}\ \forall\ t\ \in [0;\ 1] \\ HEP_{\text{nom}}(t) = 1 - k * e^{-\alpha(t\ -1)^{\beta}}\ \forall\ t\ \in ]1;\ \infty[ \end{cases} \tag{3}$$

The value of k is calculated according to the value that the curves takes for $t$ = 1, while the parameter $\beta$ = 1.5 is deducted according to the scientific literature of the human error assessment and reduction technique (HEART) model developed by Williams [16]. The value of $\alpha$ is determined by setting the value of the function for $t$ = 8 for each GTTs. Starting from this function, it is possible to calculates the value of $\alpha$ through the inverse formulas, see Eq. (4):

$$HEP_{\text{nom}}(t) = 1 - k * e^{-\alpha(t-1)^{\beta}}\ \forall\ t\ \in ]1; \infty[ \tag{4}$$

| No. | Generic task | Limitations of unreliability (%) | $k$ ($t$ = 1) | $k$ ($t$ = 8) | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|
| 1 | Totally unfamiliar | 0.35–0.97 | 0.65 | 0.03 | 0.1661 | 1.5 |
| 2 | System recovery | 0.14–0.42 | 0.86 | 0.58 | 0.0213 | 1.5 |
| 3 | Complex task requiring high level of comprehension and skill | 0.12–0.28 | 0.88 | 0.72 | 0.0108 | 1.5 |
| 4 | Fairly simple task performed rapidly or given scant attention | 0.06–0.13 | 0.94 | 0.87 | 0.0042 | 1.5 |
| 5 | Routin, highly practised | 0.007–0,045 | 0.993 | 0.955 | 0.0021 | 1.5 |
| 6 | Restoring a system by following the procedures of controls | 0.008–0.007 | 0.992 | 0.993 | −5.44E−05 | 1.5 |
| 7 | Completely familiar, well designed, highly practised, routine task | 0.00008–0.009 | 0.9999 | 0.991 | 0.00005 | 1.5 |
| 8 | Respond correctly to system command even when there is an augmented or automated supervisory system | 0.00000–0.0009 | 1 | 0.9991 | 4.86E−05 | 1.5 |

**Table 1.** Generic tasks.

$\alpha$ coefficient is represented by Eq. (5), as follows:

$$\alpha = \frac{-\ln\left[\frac{k(t=8)}{k(t=1)}\right]}{(t-1)^{\beta}} \tag{5}$$

**Figure 4** shows the reliability performance according to Weibull distribution.

**Table 2** shows the $HEP_{nom}$ values for the case study, calculated for the three different generic tasks.

### 3.4. Step 4: choice of performance shaping factors (PSFs)

In the present step, PSFs were defined. PSFs allow to take into account all the environmental and behavioural factors that influence operator's cognitive behaviour. In particular, PSFs simulate different emergency scenarios. Analytically, PSFs increase the value of the error probability introducing external factors that could strain the 'decision maker'. PSFs and their values are deducted by standardized plant analysis risk-human reliability analysis (SPAR-H) method [17, 18]. **Table 3** shows the PSFs considered.

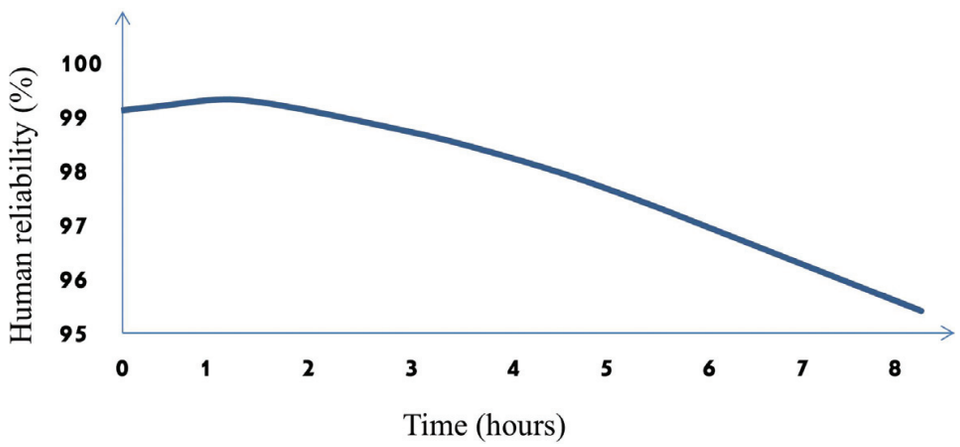


**Figure 4.** Reliability performance ($t$ = 0–8).

| | Generic task 4 | Generic task 7 | Generic task 8 |
|---|---|---|---|
| $HEP_{nom}$ ($t$ = 1) | 0.06 | 0.0001 | 0 |
| $HEP_{nom}$ ($t$ = 2) | 0.0639 | 0.0006 | 0.00005 |
| $HEP_{nom}$ ($t$ = 3) | 0.0710 | 0.0014 | 0.0001 |
| $HEP_{nom}$ ($t$ = 4) | 0.0802 | 0.0026 | 0.0003 |
| $HEP_{nom}$ ($t$ = 5) | 0.0909 | 0.0039 | 0.0004 |
| $HEP_{nom}$ ($t$ = 6) | 0.1029 | 0.0055 | 0.0005 |
| $HEP_{nom}$ ($t$ = 7) | 0.1160 | 0.0072 | 0.0007 |
| $HEP_{nom}$ ($t$ = 8) | 0.1300 | 0.0090 | 0.0009 |

**Table 2.** $HEP_{nom}$.

| PSFs | PSF level | Multipliers |
|---|---|---|
| Available time | Inadequate time | $HEP = 1$ |
| | Time available > 5× time required | 0.1 |
| | Time available > 50× time required | 0.01 |
| Stress/stressors | Extreme | 5 |
| | High | 2 |
| | Nominal | 1 |
| Complexity | High complex | 5 |
| | Moderately complex | 2 |
| | Nominal | 1 |
| | Good | 0.5 |

**Table 3.** Performance shaping factors.

| PSF | Low hazard | Moderate hazard | High hazard |
|---|---|---|---|
| **Available time** | 0.01 | 0.1 | 1 |
| **Stress** | 1 | 2 | 5 |
| **Complexity** | 1 | 2 | 5 |

**Table 4.** PSFs for the three emergency conditions.

While **Table 4** shows PSFs, defined according the three emergency conditions (see Step 1).

### 3.5. Step 5: determination *PSFcomp*

Defined PSFs and its multipliers, it is important to evaluate the overall PSF index ($PSF_{comp}$), as follows (Eq. (6)):

$$PSF_{\text{comp}} = \prod_{i=1}^{n} PSFi \tag{6}$$

$PSF_{comp}$ index summarizes the weight of each influencing factor with respect to the actions/decisions operator. **Table 5** describes the values for the $PSF_{comp}$ according to three emergencies levels.

### 3.6. Step 6: determination $HEP_{cont}$

The last step consists to contextualize the probability error analysis, defined as follows (Eq. (7)):

| | Low hazard | Moderate hazard | High hazard |
|---|---|---|---|
| $PSF_{comp} = (PSF_1 \times PSF_2 \times PSF_3)$ | 0.01 | 0.4 | 25 |

**Table 5.** $PSF_{comp}$.

$$HEP_{\text{cont}} = \frac{HEP_{\text{nom}} * PSF_{\text{comp}}}{HEP_{\text{nom}} * (PSF_{\text{comp}} - 1) + 1} \tag{7}$$

The value of $HEP_{\text{cont}}$ provides the level of probability of error of the decision maker, in function of influencing factors. The $HEP_{\text{cont}}$ value increases with the increase of time. The $HEP_{\text{cont}}$ is closely linked to two parameters. The first one is the time ($1 \leq t \leq 8$). The second one is the value of PSFs. In other words, $HEP_{\text{cont}}$ value increases with the time and increases with the increase of the 'danger' of the emergency scenario assumed. **Table 6** shows $HEP_{\text{cont}}$ considering generic task 4 and different emergency levels.

From a graphic point of view, **Figure 5** shows the trend of $HEP_{\text{cont}}$ the worst case scenario.

| Generic task | $HEP_{\text{nom}}$ ($t$) | | $HEP_{\text{cont}}$ | | |
|---|---|---|---|---|---|
| | | | **Low hazard** | **Moderate hazard** | **High hazard** |
| **Fairly simple task performed rapidly or given attention** | $t = 1$ | 0.0600 | 6.38E−04 | 2.49E−02 | 6.15E−01 |
| | $t = 2$ | 0.0639 | 6.82E−04 | 2.66E−02 | 6.31E–01 |
| | $t = 3$ | 0.0710 | 7.64E−04 | 2.97E−02 | 6.56E–01 |
| | $t = 4$ | 0.0802 | 8.71E−04 | 3.37E−02 | 6.86E−01 |
| | $t = 5$ | 0.0909 | 9.99E−04 | 3.85E−02 | 7.14E–01 |
| | $t = 6$ | 0.1029 | 1.15E−03 | 4.39E02 | 7.41E−01 |
| | $t = 7$ | 0.1160 | 1.31E−03 | 4.99E−02 | 7.66E−01 |
| | $t = 8$ | 0.1300 | 1.49E03 | 5.64E−02 | 7.89E−01 |

**Table 6.** $HEP_{\text{cont}}$.

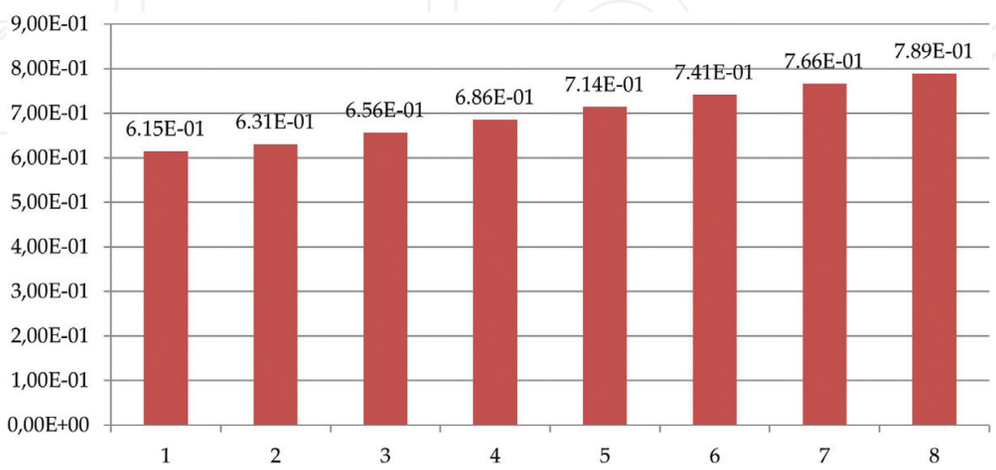


**Figure 5.** $HEP_{cont}$ (high hazard).

### 3.7. Step 7: determination $HEP_{contw/d}$

As stated, PSFs have been modelled starting from PSFs proposed by the SPAR-H methodology. It is worthy to note that the values attributable to each PSFs are proportional to the severity of their impact. However, this index does not take into account, any interdependencies among PSFs chosen. To cover this gap, a correlation among PSFs, developed by Boring [19], analysing 82 incidental reports in the US nuclear plants have been taken into account for our case study, as shown in **Table 7**.

Thus, HEP index is given by Eq. (8):

$$HEP_{\text{Task1}}|\{PSF_i; PSF_j\} = HEP_{\text{Task1}}|PSF_i + (1 - k_{ij}) * HEP_{\text{Task1}}|PSF_j \tag{8}$$

where

- $PSF_i$ means the value obtained by the calculation $PSF_{comp}$ (with independent PSFs);
- $PSF_j$ indicates the additional PSF, which is supposed to be dependent on the previous;

| For diagnosis | Available time | Stress/ stressors | Complexity | Experience/ training | Procedures | Ergonomics/ HMI | Fitness for duty | Work processes |
|---|---|---|---|---|---|---|---|---|
| Available time | 1 | | | | | | | |
| Stress/stressors | 0.67* | 1 | | | | | | |
| Complexity | −0.02 | 0.15* | 1 | | | | | |
| Experience/ training | −0.03 | 0.06 | 0.21* | 1 | | | | |
| Procedures | −0.07 | 0.01 | 0.25* | 0.28* | 1 | | | |
| Ergonomics/HMI | 0.01 | 0.06 | −0.05 | 0.20* | 0.09 | 1 | | |
| Fitness for duty | −0.03 | 0.03 | −0.03 | 0.18* | 0.09 | 0.44* | 1 | |
| Work processes | −0.06 | 0 | 0.24* | 0.55* | 0.36* | 0.15* | 0.10 | 1 |
| **For action** | | | | | | | | |
| Available time | 1 | | | | | | | |
| Stress/stressors | 0.50* | 1 | | | | | | |
| Complexity | 0.38* | 0.35* | 1 | | | | | |
| Experience/ training | 0.31* | 0.21* | 0.32* | 1 | | | | |
| Procedures | 0.05 | −0.01 | 0.12* | 0.08* | 1 | | | |
| Ergonomics/HMI | 0.10* | 0.04 | 0.08* | 0.08* | 0.29* | 1 | | |
| Fitness for duty | 0.20* | 0.29* | 0.22* | 0.17* | 0.12* | 0.27* | 1 | |
| Work processes | 0 | 0.13* | 0.16* | 0.20* | 0.35* | 0.12* | 0.15* | 1 |

Asterisk (*) indicated significant correlations with p value <0.05.

**Table 7.** PSFs correlation developed by Boring.

- $k_{ij}$ is the value of the parameter representative of the inter-dependent between two (or more) PSFs.

To quantify the influence of PSFs, the HEPcont w/d is calculated through Eq. (9):

$$HEP_{\text{cont w/d}} = HEP_{\text{nom}} * [PSF_{\text{i}} + (1 - k_{ij}) * PSF_j] \tag{9}$$

Referring to our case study, HEPcont w/d is given by Eq. (10):

$$HEP_{contw/d}(t = 4) \vee \{PSF_i; PSF_j\} = \frac{0.0802 * [25 + (1 - k_{ij}) * 3]}{0.0802 * [25 + (1 - k_{ij}) * 3 - 1] + 1} \tag{10}$$

The attribution of the $k_{ij}$ value can be assumed, considering the value of the correlation coefficients, or even based on a combination of expert judgment and data extrapolated from previous observations. The correlation between experience/training and the others PSFs is assumed moderate. In particular, a decision tree (**Figure 6**) is defined in order to choose the best value for $k_{ij}$. The final result is $k_{ij} = 0.6$.

Then, the value of HEPcont w/d is given by Eq. (11):

$$HEP_{cont\frac{w}{d}}(t = 4) \vee \{PSF_i; PSF_j\} = \frac{0.0802 * [25 + (1 \quad - 0.6) * 3]}{0.0802 * [25 + (1 \quad - 0.6) * 3 \quad - 1] + 1} = 0.695 \tag{11}$$

**Table 8** shows the new values for PSFs and **Table 9** shows the values of HEPcontw/d for the fourth generic task.

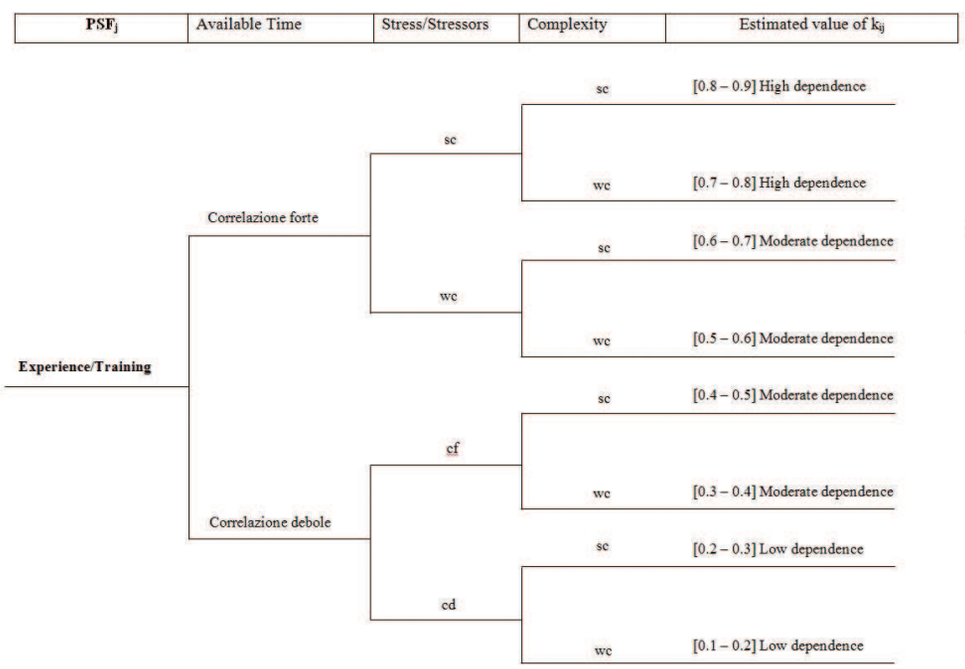


**Figure 6.** Decision tree.

| PSF | Low hazard | Moderate hazard | High hazard |
|---|---|---|---|
| **Available time** | 0.01 | 0.1 | 1 |
| **Stress** | 1 | 2 | 5 |
| Complexity | 1 | 2 | 5 |
| **Experience/training** | 0.5 | 1 | 3 |

**Table 8.** New PSFs value.

| Generic task | *HEP*nom (*t*) | *HEP*cont w/d | | | |
|---|---|---|---|---|---|
| | | Low hazard | | Moderate hazard | High hazard |
| **Fairly simple task performed rapidly or given attention** | $t = 1$ | 0.0600 | 1.32E−02 | 4.86E−02 | 6.26E−01 |
| | $t = 2$ | 0.0639 | 1.41E−02 | 5.18E−02 | 6.42E−01 |
| | $t = 3$ | 0.0710 | 1.58E−02 | 5.77E−02 | 6.67E−01 |
| | $t = 4$ | 0.0802 | 1.80E−02 | 6.52E−02 | 6.95E−01 |
| | $t = 5$ | 0.0909 | 2.06E−02 | 7.41E−02 | 7.24E−01 |
| | $t = 6$ | 0.1029 | 2.35E−02 | 8.41E−02 | 7.50E−01 |
| | $t = 7$ | 0.1160 | 2.68E−02 | 9.50E−02 | 7.75E−01 |
| | $t = 8$ | 0.1300 | 3.04E−02 | 1.07E−01 | 7.97E−01 |

**Table 9.** $HEP_{\text{contw/d}}$.

### 3.8. Step 8: rating $HEP_{nom}$ after the 8th hour of work

In this step, the analysis was extended over the 8 hours of work. **Figure 7** shows the reliability comprised between 0 and 16 hours of work.

For analysis after 8 hours, the only thing that changes is the $k$ factor. For the analysis after 8 hours, we used the factor $k$ ($t = 8$), while for the first 8 hours, we considered the factor $k$ ($t = 1$). The remaining steps are unchanged. The use of a new factor $k$ ($t = 8$) defines a raising of operator fatigue. After the 8th hour of work, there is a step on the reliability of the operator. **Table 10** represents the $\text{HEP}_{\text{cont}}$ values for the first 16 hours of work.

### 3.9. Step 9: determination $HEP_{\text{tot}}$: discussion and results

During emergency situations, the work shifts may be longer than 8 hours of work, so the operators are subject to high stress loads. For this reason, we considered the variation of PSFs with the passage of time. To calibrate the uncertainty due to the change of time using the success likelihood index method (SLIM) [20], the worse conditions of the work of the operators, through the use of the SLIM methodology, is analysed. The operator fatigue is the first element

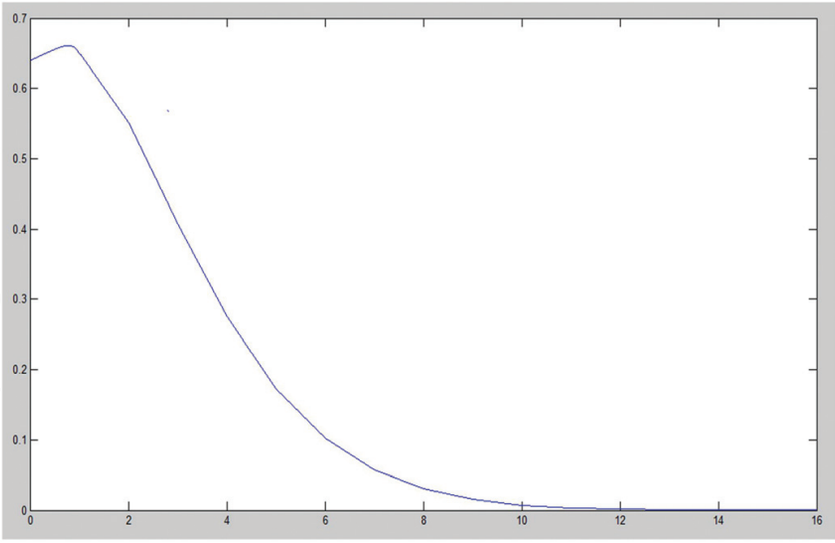


**Figure 7.** Reliability performance ($t$ = 0–16).

| Generic task | $HEP_{nom}$ ($t$) | | $HEP_{cont}$ | | |
|---|---|---|---|---|---|
| | | | **Low hazard** | **Moderate hazard** | **High hazard** |
| **Fairly simple task performed rapidly or given attention** | ***t* = 1** | 0.0600 | 6.38E−04 | 2.49E−02 | 6.15E−01 |
| | ***t* = 2** | 0.0639 | 6.82E−04 | 2.66E−02 | 6.31E−01 |
| | ***t* = 3** | 0.0710 | 7.64E−04 | 2.97E−02 | 6.56E−01 |
| | ***t* = 4** | 0.0802 | 8.71E−04 | 3.37E−02 | 6.86E−01 |
| | ***t* = 5** | 0.0909 | 9.99E−04 | 3.85E−02 | 7.14E−01 |
| | ***t* = 6** | 0.1029 | 1.15E−03 | 4.39E−02 | 7.41E−01 |
| | ***t* = 7** | 0.1160 | 1.31E−03 | 4.99E−02 | 7.66E−01 |
| | ***t* = 8** | 0.1300 | 1.49E−03 | 5.64E−02 | 7.89E−01 |
| | ***t* = 9** | 0.2085 | 2.63E−03 | 9.53E−02 | 8.68E−01 |
| | ***t* = 10** | 0.2228 | 2.86E−03 | 1.03E−01 | 8.78E−01 |
| | ***t* = 11** | 0.2377 | 3.11E−03 | 1.11E−01 | 8.86E−01 |
| | ***t* = 12** | 0.2530 | 3.38E−03 | 1.19E−01 | 8.94E−01 |
| | ***t* = 13** | 0.2687 | 3.66E−03 | 1.28E−01 | 9.02E−01 |
| | ***t* = 14** | 0.2847 | 3.96E−03 | 1.37E−01 | 9.09E−01 |
| | ***t* = 15** | 0.3010 | 4.29E−03 | 1.47E−01 | 9.15E−01 |
| | ***t* = 16** | 0.3175 | 4.63E−03 | 1.57E−01 | 9.21E−01 |

**Table 10.** $HEP_{cont}$ ($t$ = 1–16).

to consider. Fatigue is quantified using the standard sleepiness scale (SSS) [21]. The scale is represented in **Table 11**. The result is a score related to drowsiness.

The next step is to define the incidence of each PSFs relative to fatigue (W). The values are reported in percentage scale. The sum of the weights must give 100%. At this point, it calculates the modified SLI index using Eq. (12):

$$SLI_j = \sum_i R_{ij} W_i \tag{12}$$

**Table 12** shows the SLI index calculation for generic task 4, considering the presented PSFs.

The SLI index must be transformed into *HEP*. It is assumed that between SLI and *HEP* exist the relation as follows (Eq. (13)):

$$\log(P) = aSLI + b \tag{13}$$

where $P$ represents the *HEP* value and $a$ and $b$ are constants. At this point it is necessary to calibrate the value of the constants to obtain the value of *HEP*. To do this, a comparative comparison between the values of SLI is carried out. In the previous step, *HEP* index values for $1 < t < 16$ have been obtained. In this step, the extreme values of that range are used, as follows:

- $HEP_{min}$ = 6,38E−04 ➔ $t$ = 1 (low hazard) $SLI$ = 1
- $HEP_{max}$ = 9,21E−01 ➔ $t$ = 16 (high hazard) $SLI$ = 7

| Degree of sleepiness | Scale rating (*R*) |
|---|---|
| Feeling active, vital, alert, or wide awake | 1 |
| Functioning at high levels, but not at peak; able to concentrate | 2 |
| Awake, but relaxed; responsive but not fully alert | 3 |
| Somewhat foggy, let down | 4 |
| Foggy; losing interest in remaining awake; slowed down | 5 |
| Sleepy, woozy, fighting sleep; prefer to lie down | 6 |
| No longer fighting sleep, sleep onset soon; having dream-like thoughts | 7 |

**Table 11.** Stanford sleepiness scale.

| Weighting ($W_k$) | PSFs | Rating ($R_k$) | SLI = W·R |
|---|---|---|---|
| 0.2 | Available time | 4 | 0.8 |
| 0.5 | Stress | 4 | 2 |
| 0.3 | Complexity | 4 | 1.2 |
| Fairly simple task performed rapidly or given attention ($t$ = 10) ∑ 4. | | | |

**Table 12.** SLI for the GTT 4.

Using the inverse formula, the final equation that calculates the *HEP* index for each task is obtained. The formula is defined according to Eq. (14):

$$log(HEP) = aSLI + b \tag{14}$$

Here is a mathematical formulation that allows to define $a$ and $b$:

$$\begin{cases} log_{10}(0.000638) = aSLI + b \\ log_{10}(0.921) = aSLI + b \end{cases} \begin{cases} -3.19 = a + b \\ -0.035 = a * 7 + b \end{cases} \begin{cases} b = -3.19 - a \\ 7a = -0.035 - b \end{cases}$$
$$\begin{cases} b = -3.19 - a \\ 7a = -0.035 + 3.19 + a \end{cases} \begin{cases} b = -3.19 - a \\ 6a = -0.035 + 3,19 \end{cases} \begin{cases} a = 0.52 \\ b = -3.71 \end{cases} \tag{15}$$

Having obtained the values $a$ and $b$, the formulation for the final calculation of the index *HEP* becomes:

$$\begin{aligned} &log(HEP) = 0.52\text{SLI} - 3.71, \ \text{SLI} \ = \ 4 \\ &log(HEP) = -1.63 \rightarrow HEP = 0.023 \end{aligned} \tag{16}$$

It is possible to note that the value of *HEP* is lower compared to the previous *HEP* calculated for $t$ ranging from 1 to 16. In order to obtain a more accurate model a calibration is carried out. **Figure 8** compares the $HEP_{nom}$ curve with the calibrated *HEP* curve.

$HEP_{tot}$ value is calculated by adding up the values $HEP_{nom}$ that the *HEP* values calculated with SLI calibration ($\Delta HEP$). $HEP_{tot}$ value replaces the model EHEA the $HEP_{\text{nom}}$ value, as shown in **Table 13**.

**Figure 9** shows the graph of the $HEP_{\text{tot}}$. It assumes to model the increase of the $HEP_{\text{nom}}$ nominal value, to which are summed the corresponding $\Delta HEP$ values, starting from $t = 8$.

The main result of the model shows how the human reliability depends on the time and how it is important to consider operator performance beyond the canonical 8 hours.

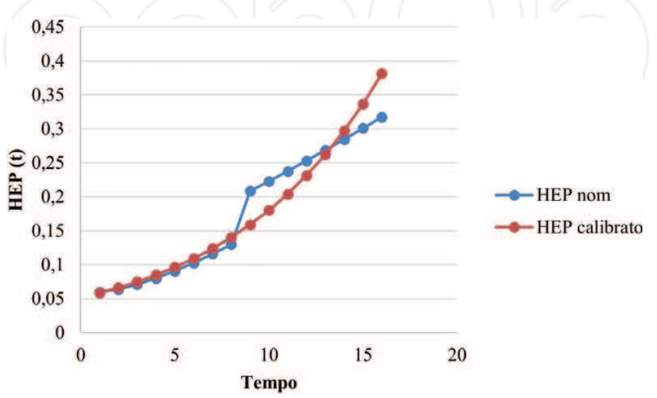


**Figure 8.** $HEP_{nom}$—calibrated *HEP* (SLI).

| EHEA | | | SLIM | | |
|---|---|---|---|---|---|
| ***HEP*nom** | **$Log_{10}$ (*HEP* nom)** | ***ΔHEP*** | **$Log_{10}$ (*HEP* nom)** | **SLI** | ***HEP*tot** |
| 0.060 | −1.221 | 0.0585 | −1.232 | 1 | 0.118 |
| 0.063 | −1.194 | 0.0585 | −1.232 | 1 | 0.122 |
| 0.071 | −1.148 | 0.0585 | −1.232 | 1 | 0.129 |
| 0.080 | −1.095 | 0.0663 | −1.178 | 2 | 0.146 |
| 0.090 | −1.041 | 0.0663 | −1.178 | 2 | 0.157 |
| 0.102 | −0.987 | 0.0663 | −1.178 | 2 | 0.169 |
| 0.116 | −0.935 | 0.0751 | −1.124 | 3 | 0.191 |
| 0.130 | −0.886 | 0.0751 | −1.124 | 3 | 0.205 |
| 0.208 | −0.680 | 0.0751 | −1.124 | 3 | 0.283 |
| 0.222 | −0.652 | 0.0851 | −1.069 | 4 | 0.307 |
| 0.237 | −0.623 | 0.0851 | −1.069 | 4 | 0.322 |
| 0.253 | −0.596 | 0.0964 | −1.015 | 5 | 0.349 |
| 0.268 | −0.570 | 0.0964 | −1.015 | 5 | 0.365 |
| 0.284 | −0.545 | 0.1093 | −0.961 | 6 | 0.394 |
| 0.301 | −0.521 | 0.1093 | −0.961 | 6 | 0.410 |
| 0.317 | −0.498 | 0.1239 | −0.906 | 7 | 0.441 |

**Table 13.** $HEP_{tot}$.

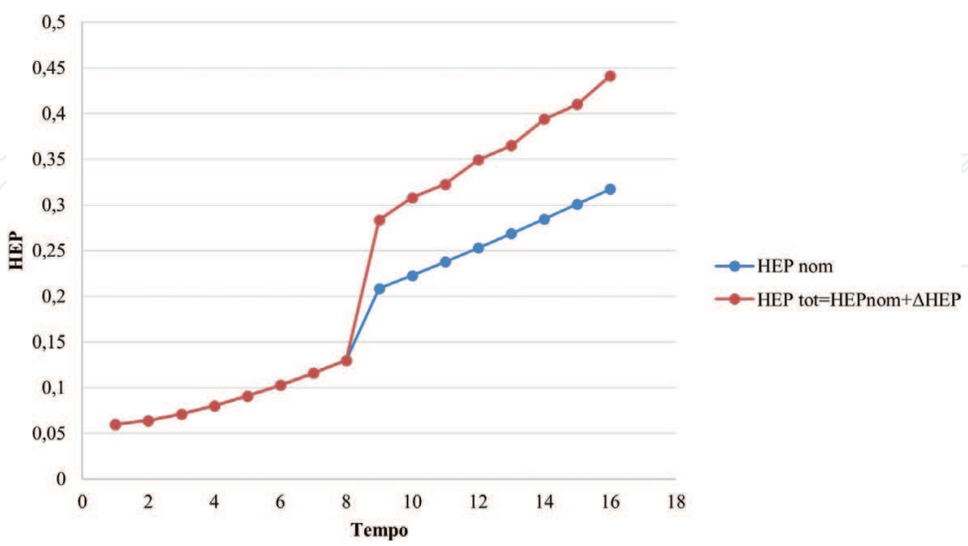


**Figure 9.** $HEP_{nom}$—$HEP_{tot}$.

## 4. Conclusion

In general, the modelling approaches used in HRA are focused to describe sequential low-level tasks, which are not the main source of systemic errors. On the contrary, we believe that it is important to analyse in deeper human behaviour that causes errors in order to develop managerial practices that could be applied to reduce the failures that occur at the interface of human behaviour and technology. Thus, the aim of this work was to develop an innovative methodology for human reliability analysis in emergency scenarios. A hybrid model that integrates the advantages of the following methodologies: human error assessment and reduction technique (HEART), standardized plant analysis risk-human reliability analysis (SPAR-H) and Success Likelihood Index Method (SLIM) has been proposed. The key point that we have been trying to convey in this research is the analysis of all environmental and behavioural factors that influence human reliability. Results obtained from the analysis of a real case study give an empirical contribution and a theoretical contribution referring to the framework used to detect human error in risk and reliability analysis. Furthermore, the study could be a useful perspective for the entire academic community to make the community fully aware of new assumptions in human reliability analysis.

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