CHEMICAL ENGINEERING TRANSACTIONS
VOL. 43, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

**ISBN** 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543208

# Human Error Probability Estimation in ATEX-HMI Area Classification: from THERP to FUZZY CREAM

Jie Geng[*a,b], Salvina Murè[a], Baldissone Gabriele[b], Gianfranco Camuncoli[a], Micaela Demichela[b]

[a] ARIA s.r.l. – Corso Mediterraneo 140 -10129 Torino, Italia
[b] SAfeR, Dipartimento di Scienza Applicata e Tecnologia, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italia
jie.geng@aria.to.it

ATEX (explosive atmosphere) risk assessment is required when any equipment or system can potentially cause explosive atmospheres. Although many operations are performed by operators, influences from human and organizational factors (HOFs) are mostly neglected. In order to address HOFs influence, the ATEX-HMI (Human-Machine Interaction) methodology is proposed: it aims at integrating HOFs into each step of the standard ATEX risk assessment. The first step faced is Area classification: the ATEX-HMI methodology introduces the Human Error Probability (HEP) into the zone calculation procedure. Human Reliability Analysis (HRA) is the main method for the HEP assessment, thus two HRA methods were applied for the ATEX-HMI methodology. The first one, THERP, demonstrated an efficient quantitative precision, but it was not easily applicable to real industries. Then, the Cognitive Reliability and Error Analysis Method (CREAM) was adopted, together with a complementary FUZZY application for quantitative analysis. The present paper introduces the FUZZY CREAM application, also showing a comparative analysis of THERP and FUZZY CREAM, on the basis of a food plant case study.

## 1. Introduction

ATEX (explosive atmosphere) risk assessment is required when an equipment or system can potentially cause explosive atmospheres. The standard ATEX risk assessment is a semi-quantitative approach, based on the following indexes: 1) likelihood of an explosive atmosphere occurring, 2) likelihood of ignition sources present on site, 3) consequences. Influences by human and organizational factors (HOFs) are mostly neglected from the standard ATEX risk assessment, although many operations are performed by operators (e.g. maintenance activity, as in Demichela et al., 2014, that could even bring to major accidents, as in Piccinini & Demichela, 2012; Leva et al., 2012). In order to deal with HOFs influence, ATEX-HMI (Human-Machine Interaction) methodology was proposed by the authors and is actually in progress. Figure 1 shows the ATEX-HMI risk assessment framework with the HOFs integration: for each step of the standard ATEX risk assessment, human error probability (HEP) is introduced. In this way, the final result of the risk assessment $R_{HOF}$ will be influenced by the values of $P_{HOF}$, $C_{HOF}$ and $D'_{HOF}$. In an early phase (Geng et al., 2014), a task-dominant Human Reliability Analysis (HRA) method - the Technique for Human Error Rate Prediction (THERP, Swain and Guttmann, 1983) - was introduced for the HEP assessment. Nevertheless, it revealed some issues during the on-site application among real industries:

1) The lack of data related to actual human performances challenges the accuracy of the HEP prediction. Indeed the data made available by THERP simulator (Swain, 1990) are designed for nuclear plants, and it is difficult to adapt these raw data to other types of industries.
2) The Performance Shaping Factors (PSFs), such as organizational factors, cultural differences, and irrational behavior are not adequately treated in THERP, and neither specific rules are given to assess the states of these PSFs and their effects on HEP.

Please cite this article as: Geng J., Mure S., Baldissone G., Camuncoli G., Demichela M., 2015, Human error probability estimation in atex-hmi area classification: from therp to fuzzy cream, Chemical Engineering Transactions, 43, 1243-1248 DOI: 10.3303/CET1543208

3) End users generally are Health & Safety Experts, whose professional background is not related to human factors domain. The request to assign values in order to obtain the HEP can be very complex and strongly increases HSEs workload: for one single task, 27 tables have to be compiled. Also, HSEs' insufficient knowledge in Human Factors may lead to uncertain HEP predictions.

Therefore, the objective of the further phase of this study was to identify an easier and more applicable technique for the HEP estimation, and to integrate it into the 1st step of the standard ATEX risk assessment procedure (Area classification).

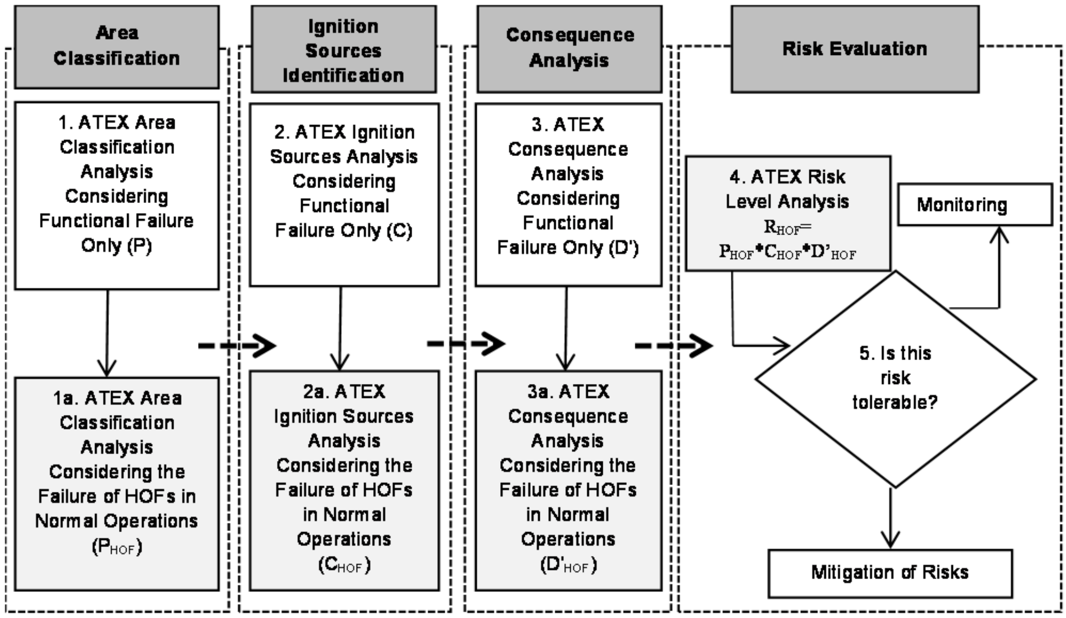


*Figure 1. The Framework of ATEX-HMI Risk Assessment Methodology (Geng et al., 2014)*

## 2. Integration of HOFs into ATEX-HMI Area Classification

Standard ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures; its first step, Area classification, generally includes: 1) the identification of release sources - each item of the process equipment which contains a flammable material is considered as a potential release source; 2) assessment of the internal and external zones of the identified emission sources, on the basis of release rate, concentration, velocity, ventilation and other factors (such as prevention measures). Italian Guidelines CEI 31-35, 2012; & CEI 31-56, 2007 provide also another method to conduct the Area classification, based on probability values (see Table 1); this is allowed only when the statistical data on the probability of explosive atmosphere occurring are available and reliable. However, Table 1 can be also employed in reverse, to assess probability ranges starting from normal Area classification. In fact, ATEX-HMI area classification takes advantage of Table 1 indexes to integrate the Human Error Probability (HEP) into zone prediction, so that the final probabilistic safety assessment (PSA) will be the sum of the probabilities corresponding to the obtained zones and the HEP.

*Table 1: Evaluation Criteria of the ATEX-HMI Area Classification (CEI 31-35, 2012; & CEI 31-56, 2007)*

| Area Classification | Probability of Explosive Atmosphere Occurring in 365 days | Descriptor |
|---|---|---|
| Zone 0/20 | $10^{-1} < P$ | Explosive atmosphere is continuously present, for long periods or frequently. |
| Zone 1/21 | $10^{-3} < P \leq 10^{-1}$ | Explosive atmosphere is sporadically present, during normal operations. |
| Zone 2/22 | $10^{-5} < P \leq 10^{-3}$ | Explosive atmosphere is not present during normal operations, or infrequently present, for a short period. |
| Zone NE | $P < 10^{-5}$ | Neglectable |

## 3. HEP Estimation: from THERP to FUZZY CREAM

### 3.1 CREAM - Cognitive Reliability and Error Analysis Method

After THERP application, a cognition-dominant HRA method was chosen: CREAM - Cognitive Reliability and Error Analysis Method. This method covers technical, human and organizational factors, and provides a relatively stable HEP output; also, it was designed for different types of industries (Chandler, et. al, 2006). CREAM defines 9 Common Performance Conditions (CPCs) as Performance Shaping Factors (PSFs), and provides a two-level method to calculate Human Error Probability (HEP): the basic method and the extended method. The basic method uses task analysis to identify human actions, and assesses the Common Performance Conditions (CPCs) by judging the expected effects and making a total or combined score of them with the triplet [$\sum_{reduced}$, $\sum_{not\ significant}$, $\sum_{improved}$]. Final results are interpreted through a control mode matrix: 4 possible control modes (Strategic, Tactical, Opportunistic, Scrambled), defined by the Contextual Control Mode - COCOM, can be determined. If the basic method is not sufficient, CREAM provides the extended method to produce specific action failure probabilities (Hollnagel, 1998).

### 3.2 FUZZY CREAM

Starting from CREAM basic method, Konstandinidou et al. (2006) introduced FUZZY CREAM as a complementary methodology to assess the HEP. For this study, a dedicated tool was developed to apply FUZZY CREAM, based on both contributions from Konstandinidou et al. (2006) and Monferini et al. (2013). Meanwhile, the Fuzzy Logic Toolbox in Matlab® was used for the result validation.

*Step 1 - Fuzzification*

Fuzzy logic starts with the concept of a fuzzy set. In practice, if X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$A = \{x, \mu_A(x) \mid x X\}$

$\mu_A(x)$ is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1. In this FUZZY CREAM tool, triangular membership function was used as straight lines to describe the distributions of each level of a fuzzy input set. The 9 CREAM CPCs mentioned in Section 3.1. were used to build the input fuzzy sets (see Table 2) and also the output fuzzy sets were derived from the four control modes provided by COCOM (see Table 3).

*Step 2 - Fuzzy inference*

Fuzzy inference is a method that interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. The primary mechanism is doing a list of “if-then” rules. Since in fuzzy logic the truth of any statement is a matter of degree, min-max operations are applied to resolve the statement. In FUZZY CREAM, the rules are constructed in simple linguistic terms and Mamdani's fuzzy inference method is applied. Furthermore, 46656 rules are generated. Here the first rule is presented as an example: “*IF* Adequacy of Organization is very efficient, *AND* Working Conditions is advantageous, *AND* Adequacy of MMI and Operational Support is supportive, *AND* Availability of Procedures / Plans is appropriate, *AND* Number of Simultaneous Goals is fewer than capacity, *AND* Available Time is adequate, *AND* Time of Day (Circadian Rhythm) is unadjusted Night-time, *AND* Adequacy of Training and Experience is adequate with high experience, *AND* Crew Collaboration Quality is very efficient, *THEN* output is Strategic control mode.”

*Step 3 - Defuzzification*

Defuzzification transforms the final aggregated output fuzzy sets into a single numerical value; the developed FUZZY CREAM tool adopted *Centroid method* for it. The output from Step 2 composes an aggregated area; *Centroid defuzzification* allows to return the center of area under the curve, which is the HEP.

*Step 4 -Validation of Results by Matlab®*

Fuzzy logic toolbox in Matlab® provides an alternative way to gain HEP from FUZZY CREAM. It was used to validate the result derived from FUZZY CREAM tool application.

*Table 2. CPCs in CREAM as FUZZY input sets (Konstandinidou et al., 2006; Monferini et al. 2013)*

| Inputs | | Range | Fuzzy Sets | Level/Descriptors | Effect | Membership Level Intervals | |
|---|---|---|---|---|---|---|---|
| CPC 1 | Adequacy of Organization | [0,100] | 4 | Very Efficient | Improved | MF1 | 70-100 |
| | | | | Efficient | Not significant | MF2 | 40-90 |
| | | | | Inefficient | Reduced | MF3 | 10-60 |
| | | | | Deficient | Reduced | MF4 | 0-25 |
| CPC 2 | Working Conditions | [0,100] | 3 | Advantageous | Improved | MF1 | 70-100 |
| | | | | Compatible | Not significant | MF2 | 20-80 |
| | | | | Incompatible | Reduced | MF3 | 0-30 |

| Inputs | | Range | Fuzzy Sets | Level/Descriptors | Effect | Membership Level Intervals | |
|---|---|---|---|---|---|---|---|
| CPC 3 | Adequacy of MMI and Operational Support | [0,100] | 4 | Supportive<br>Adequate<br>Tolerable<br>Inappropriate | Improved<br>Not significant<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3<br>MF4 | 70-100<br>40-90<br>10-60<br>0-25 |
| CPC 4 | Availability of Procedures / Plans | [0,100] | 3 | Appropriate<br>Acceptable<br>Inappropriate | Improved<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3 | 70-100<br>20-80<br>0-30 |
| CPC 5 | Number of Simultaneous Goals | [0,100] | 3 | Fewer than capacity<br>Matching current capacity<br>More than capacity | Not significant<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3 | 70-100<br>20-80<br>0-30 |
| CPC 6 | Available Time | [0,100] | 3 | Adequate<br>Temporarily inadequate<br>Continuously inadequate | Improved<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3 | 70-100<br>20-80<br>0-30 |
| CPC 7 | Time of Day (Circadian Rhythm) | [0,24] | 3 | Night-time, (unadjusted)<br>Day-time, (adjusted)<br>Night-time, (unadjusted) | Reduced<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3 | 16-24<br>8-17<br>0-9 |
| CPC 8 | Adequacy of Training and Experience | [0,100] | 3 | Adequate, High Experience<br>Adequate, Limited Experience<br>Inadequate | Improved<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3 | 70-100<br>20-80<br>0-30 |
| CPC 9 | Crew Collaboration Quality | [0,100] | 4 | Very efficient<br>Efficient<br>Inefficient<br>Deficient | Improved<br>Not significant<br>Not significant<br>Reduced | MF1<br>MF2<br>MF3<br>MF4 | 70-100<br>40-90<br>10-60<br>0-25 |

*Table 3. Control modes with logarithm format as Fuzzy output sets*

| | UOD | Number of Fuzzy Sets | Level/ Descriptors | HEP Ranges | Membership Level Intervals *(Logarithm Format)* |
|---|---|---|---|---|---|
| Action Failure Probability | [0,1] | 4 | Strategic | $0.5 \times 10^{-5} < P < 1.0 \times 10^{-2}$ | -5.3 to -2.3 |
| | | | Tactical | $1.0 \times 10^{-3} < P < 1.0 \times 10^{-1}$ | -3.3 to -1.3 |
| | | | Opportunistic | $1.0 \times 10^{-2} < P < 0.5 \times 10^{0}$ | -2.3 to -0.3 |
| | | | Scrambled | $1.0 \times 10^{-1} < P < 1.0 \times 10^{0}$ | -1.3 to 0 |

## 4. Application of FUZZY CREAM

FUZZY CREAM tool was applied to a case study from a food manufacturing company, which produced food stabilizers, ingredients, starches and gums. The ATEX Area Classification identified 44 emission sources; among them, a dust cartridge filter was chosen to analyse the difference between standard ATEX area classification and the ATEX-HMI area classification. According to the instruction manual, the dust cartridge filter needed to be regularly replaced, depending on the frequency of use. Lacking or failure of the replacement procedure can cause a dust surplus inside the filter that could break and produce external explosive atmospheres. The initial area classification results for the filter were: zone 20 (dirty side) and zone 22 (clean side) inside, and zone 22 outside. The evaluation assumed that operators or maintainers always replaced the filter in the correct way. Thus, the initial probability range of explosive atmosphere occurring in the area around the filter was $10^{-3} \geq P > 10^{-5}$ in 365 days. However, the calculated probability range did not take into account the human failures in the replacement phase, thus FUZZY CREAM tool was applied to estimate the Human Error Probability (HEP). The 9 CPCs values were estimated by the company EHS experts, and they were used to constitute the input vector for FUZZY CREAM application. Figure 2, reported in the following page, shows the tool interface for the 9 CPCs membership functions. Then, FUZZY CREAM tool assessed the HEP as explained in Section 3.2. The HEP output obtained for the case study was $1.58 \times 10^{-2}$. After the application of FUZZY CREAM tool, the probability of explosive atmosphere occurring in 365 days resulted as the sum of the HEP value ($1.58 \times 10^{-2}$) and the initial probability value ($10^{-3} \geq P > 10^{-5}$): the probability range changed into $10^{-1} \geq P > 10^{-3}$. As a consequence, also the area classification was modified: inside the filter remained the zone 20 (dirty side) and zone 22 (clean side), while the outside area was classified as zone 21, instead of zone 22 (see Table 4). This result shows that the risk of explosive atmosphere occurring is potentially higher than that calculated by the standard ATEX area classification.

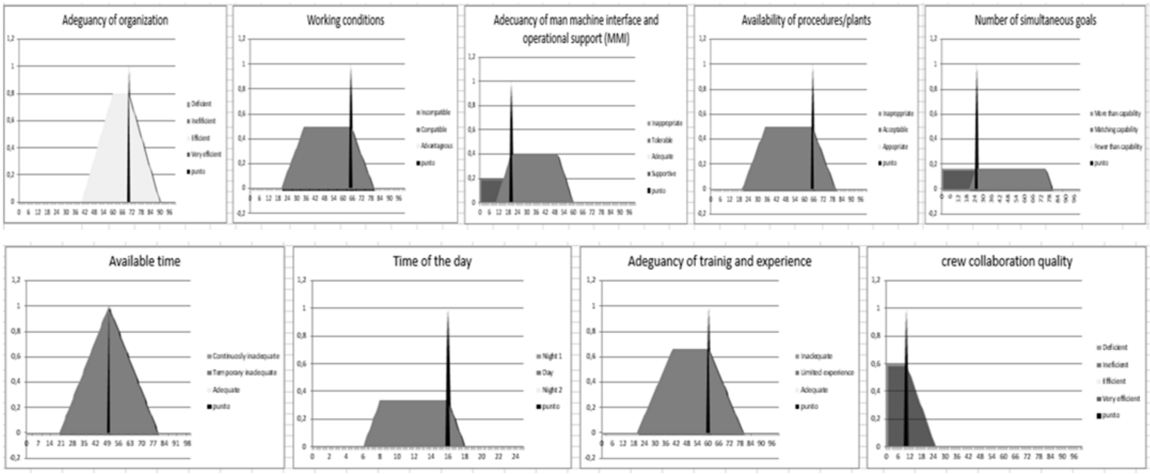


*Figure 2. Interface of FUZZY CREAM tool of the input vector: [70 65 20 65 25 50 16 60 10]*

*Table 4: ATEX-HMI Area Classification Assessment Results*

| Emission Source | Emission Degree | Generated Zone | Assumption | HEP | Amended Zone |
|---|---|---|---|---|---|
| A Dust Cartridge Filter | Secondary | Inside Dirty Side: 20<br>Inside Clean Side: 22<br>Outside: 22 | Replace GV5 in the incorrect way | $2.43\times10^{-2}$* (THERP) | Inside Dirty Side: 20<br>Inside Clean Side: 22<br>Outside: 21 |
| | | | | $1.58\times10^{-2}$ (FUZZY CREAM) | |

Note: * the HEP value is estimated in the previous work of Geng et al. (2014).

## 5. Comparison of FUZZY CREAM and THERP

The dust cartridge filter case study was firstly subjected to THERP application (Geng et al., 2014), and then to FUZZY CREAM, as shown in Section 4; the improvements led by the second method are hereinafter explained.

1) *PSF*. THERP identifies Performance Shaping Factors (PSF) that influence HEP, but it doesn't precisely define the rules (only 3 PSFs are involved in the calculation) for their application. On the contrary, CREAM is able to consider technical, human and organizational factors, and it gives very detailed indications on how to treat Common Performance Conditions (CREAM CPCs are the equivalent to THERP PSFs).

2) *HEP assessment*. THERP requires the compiling of many tables, which need a professional background in HOFs. The two levels approach provided by CREAM allows the users to choose the basic method for HEP calculation, which is very easy to apply. Also, FUZZY CREAM tool can be easily handled by the general safety specialists, after a short training period.

3) *Time consuming*. HEP calculation in THERP needs more time, because of the tables compiling. On the contrary, the developed FUZZY CREAM tool permits to spare time, because it only requires to safety specialists to assign a judgment to the CPCs; then HEP output is generated by the tool itself.

The above mentioned considerations make clear that FUZZY CREAM is an easier tool for the direct application in real-work environments: indeed it meets the need for simple, rapid but effective tools, and therefore it can be employed in many different types of industries.

## 6. Conclusions

Neglecting HOFs influence can threaten both system safety and performance. As shown in Section 4, also for ATEX risk assessment, the assumption that operators and maintainers are constantly able to operate in a correct way can lead to area classifications that could not be conservative enough. As a consequence, unexpected events may occur. The introduction of the ATEX-HMI Risk assessment methodology, able to take into account HOFs, will allow to assess more precisely the ATEX risk, and then to adopt more effective prevention and protection measures. Until now, HOFs were integrated into the 1st step of ATEX standard Risk assessment – Area classification: the application of HRA method FUZZY CREAM permitted to introduce the

Human Error Probability, and produced more accurate results than those of the standard ATEX Risk assessment. Even if it is an early stage of the assessment, the change in the area classification showed in Section 4 can be considered an important indicator of the HOFs influence, and it could be in any case a starting point for safety managers to verify and improve their approach to safety. The research is actually proceeding in order to develop HOFs integration in each step of the ATEX Risk assessment.

**Acknowledgements**

This research was supported by INNHF project, financed under EU FP7 Marie Curie Actions Initial Training Networks-FP7-PEOPLE-2011-ITN: Project ID 289837.

**References**

Cavaliere A., Scardamaglia P., 2005, Guida all'applicazione delle Direttive ATEX. EPC S.R.L., Rome, Italy (in Italian).

Cavaliere A., 2011, Manual for the ATEX application---- Area Classification, Risk Assessment and Management of Explosive Atmospheres. EPC S.R.L., Rome, Italy, pp.331-333

CEI EN 60079-10-1, 2010, Explosive atmospheres - Classification of Areas - Explosive Gas Atmospheres, Italian Electrotechnical Committee.

CEI 31-35, 2012, Equipment for Use in the Presence of Combustible Gas – Guide for Classification of Hazardous Area, Italian Electrotechnical Committee (in Italian).

CEI 31-56, 2007, Equipment for use in the presence of combustible dust – Guide for classification of hazardous area, Italian Electrotechnical Committee (in Italian).

Chandler F. T., Chang Y. H. J., Mosleh A., Marble J. L., Boring R. L., Gertman D. I., 2006, Human Reliability Analysis Methods Selection Guidance for NASA. Retrieved from NASA website: http://www.hq.nasa.gov/office/codeq/rm/reference.htm

Demichela M., Pirani R., Leva M.C., 2014, Human Factor Analysis Embedded in Risk Assessment of Industrial Machines: Effects on the Safety Integrity Level, International Journal of Performability Engineering, 10 (5), 487-496.

Geng J., Mure S., Camuncoli G., Demichela M., 2014, Integration of HOFs into ATEX risk assessment methodology, Chemical Engineering Transactions, 36, 583-588. DOI: 10.3303/CET1436098

Hollnagel E., 1998, Cognitive Reliability and Error Analysis Method: CREAM, Oxford: Elsevier Ltd.

Konstandinidou M., Nivolianitou Z., Kiranoudis C., Markatos N., 2006, A Fuzzy Modeling Application of CREAM Methodology for Human Reliability Analysis, Reliability Engineering and System Safety, 91(6),706-716.

Leva M.C., Pirani R., De Michela M., Clancy P., 2012, Human Factors Issues and the Risk of High Voltage Equipment, Chemical Engineering Transactions, 26, 273-278. DOI: 10.3303/CET1226046

Marseguerra M., Zio Enrico, Librizzi M., 2007, Human Reliability Analysis by Fuzzy "CREAM", Risk Analysis, Vol 27 (1), pp. 137-154, DOI:10.1111/j.1539-6924.2006.00865.x

Monferini A., Konstandinidou M., Nivolianitou Z., Weber S., Kontogiannis T., Kafka P., Kay A.M, Leva M.C., Demichela M., 2013, A Compound Methodology to Assess the Impact of Human and Organizational Factors Impact on the Risk Level of Hazardous Industrial Plants. Reliability Engineering and System Safety, 119, 280-289. DOI:10.1016/j.ress.2013.04.012

Piccinini N., Demichela M., 2012, Five Dead and Five Injured in a Dimethyl Terephthalate Plant Accident: Serious Errors in the Plant Design Coupled with Incorrect Maintenance Management, Industrial and Engineering Chemistry Research, 51 (22), 7619-7627.

Swain A.D., Guttmann H.E., 1983, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, NUREG/CE-1278. US Nuclear Regulatory Commission, Washington D.C., America.

Swain A.D., 1990, Human Reliability Analysis: Need, Status, Trends and Limitations. Reliability Engineering and System Safety, 29, 301-313.