A SIMULATION MODEL OF HUMAN DECISION MAKING IN EMERGENCY CONDITIONS

Fabio De Felice[(a)], Domenico Falcone[(a)], Antonella Petrillo[(b)], Agostino Bruzzone [(c)], Francesco Longo [(d)]

[(a)] Department of Civil and Mechanical Engineering - University of Cassino and Southern Lazio, Italy
[(b)] Department of Engineering - University of Naples "Parthenope", Italy
[(c)] Simulation Team, DIME, University of Genoa, Italy
[(d)] MSC-LES, University of Calabria, Italy

[(a)]defelice@unicas.it, [(a)]falcone@unicas.it, [(b)]antonella.petrillo@uniparthenope.it, [(c)] agostino@itim.unige.it, [(d)]francesco.longo@unical.it

ABSTRACT
The optimization and automation processes taking place in industry to face globalization are significantly increasing the complexity of productive processes. The high complexity requires the adoption of sophisticated methods to manage any emergency situations that may arise in case of an accident. In this context the simulation approach is one of the most innovative tool to manage emergency conditions. Simulation tools seek to represent the different scenarios that may occur and its consequences. The objective of the present research is to develop a simulation model which analyzes emergency scenarios and the impact that the operation and man's decisions on the emergency management. The paper aims to develop a simulator model for approaching emergency management and human errors in industrial and critical infrastructure. A real case study is analyzed.

Keywords: simulation, human error, disaster management, nuclear power plant

1. INTRODUCTION
In recent decades, after the serious incidents developed in industrial plants that led to the loss of many lives, the analysis of emergency situations in critical infrastructure is becoming increasingly important (Yates and Paquette, 2010). The study of critical infrastructure is important, as the company is completely dependent on these infrastructures and emergency situations that may develop into a plant, could have disastrous consequences for the whole city and community (De Felice and Petrillo, 2011). Thus, the analysis of emergency management is carried out both for individual facilities, but also to entire neighborhoods or cities. It must first identify the causes that could lead to accidents and lock before the event and find advanced features to reduce the risk of emergency situations (Hernandez and Serrano, 2001). The study of the vulnerability of critical infrastructure is of paramount importance when considering the sociological changes, technology and economics related to privatization and globalization. Obviously the analysis of emergencies is also closely linked to the analysis of *human realiability and human behaviour*, as is the man the one who manages the emergency situation and sometimes it is the one that created it (Ra'ed and Keating, 2014).
Analysis of human reliability is a multidisciplinary problem, calling for knowledge and expertise from probabilistic safety analysis, plant design and operations, decision science, and the behavioral sciences (Hollnagel, 2002). HRA grew up in the 1960s, with the intention of modeling the likelihood and consequences of human errors (Sharit, 2012).
The researchers' great efforts to propose models of human behavior favoring numerical values of error probability in order to predict and prevent unsafe conduct are clearly evident (French *et al*., 2008).
Human reliability is a crucial element to ensure industrial plant performance and to manage situations or activities where the stress factors including physiological and psychological stressors like fear, monotonous workload, overload, and so influence on the operator. Human reliability cannot be analyzed in the same manner as that of equipment/component. The main issue with human reliability analysis (HRA) is the *uncertainty* of the data concerning human factors, together with the difficulty in modeling the human behavior (Hollnagel, 2005).
According the above considerations, we can state that nowadays, the analysis of human factors constitute a *highly interdisciplinary field* of study. But it is not yet well defined, therefore, a complete and universally accepted taxonomy of different types of human errors and causes determining them, does not exist (D'Elia *et al.*, 2013).
For this purpose, the study of emergencies management must necessarily identify all the factors that influence human realibility tithin the accident scenario and its evolution. The emergency services are complex and dynamic, as in the workplace can result in accidents (Reznek *et al.*, 2003). This is even more evident as today industrial systems are becoming more complex, therefore more and more advanced tools for the analysis of incidental situations are needed. The most used tool in different areas is the simulation, as it can be on a computer a series of accident scenarios too complex and

verify their evolution. Using the simulation approach it is possible to evaluate the impact of any changes to the system by running different scenarios. Thus, a simulation approach could be a useful tool to manage emergency operations and to assess their impact (Kuo *et al.,* 2016). The specific purpose of the present study is to develop *a simulation model* for the analysis of accident and emergency management in a nuclear power plant. This is a hot topic. In fact, the use of nuclear power to satisfy energy demand is a controversy ever since, but it has recently gained momentum due to the Fukushima disaster. For the above considerations, in our opinion, it is necessary to analyze in deeper this topic in order to propose a useful tool to manage nuclear disaster. In this context, *emergency management simulation* has become one of the most popular method of preparing decision makers for various scenarios. In this paper, a simulation model which simulates the behavior of an operator controlling a complex system during the management of accidents is described. Particular attention is paid to the theoretical foundations of the model, to its computational implementation. The approach aims to build a structure for the various kinds of cognitive functions that are performed by an operator in complex environments. This paper deals with various aspects of human behavior that can influence operator reliability, considering the environment in which operator is working. The focus is on understanding the nature of human performance variability and eventually, how to describe and analyze it.

The rest of the paper is organized as follows. In Section 2 a literature review on emergency management and simulation approach is presented. Section 3 describes the nuclear power simulation model. In Section 4 a case study is analyzed. Section 5 presents discussion and results. Finally, in Section 6, conclusions are analyzed.

2. LITERATURE REVIEW

In the literature, there are different risk-based approaches reported, ranging from the purely qualitative to the quantitative (Longo and Ören, 2008). Many authors used probabilistic risk assessment. A vast majority of tools and techniques available for the HRA are meant for high risk sectors like nuclear, petrochemical industries, and so on, applied within the context of probabilistic safety assessment (Cacciabue, 1996). In this context, it is necessary to evaluate the alternative operations that can be done to manage the situation (Brady, 2003). The underlying causes of emergency situations may be human, natural or mechanical. Human causes are mainly due to human error, natural causes are due to natural disasters such as earthquakes, tsunamis, hurricanes, etc., while the mechanical causes are due to breakdowns of machines.

There are various models for the management of emergencies. In particular it is possible to consider 2 main approaches, as follows:

a) *Operations Research,* which provides mathematical tools to support decision-making activities, coordinating activities with scarce resources in order to maximize an objective function (Shannon *et al.,* 1980);
b) *Multicriteria analysis* that analyzes a number of important aspects and decision makers that make the difficult procedure due to a single goal (De Felice *et al.,* 2016).

The evaluation of the results obtained with these methods is achieved by *simulation*. The simulation is the true representation of real systems on a virtual platform. In the literature, there are many simulation models for the management of emergencies (Bruzzone *et al.,* 2014). Some examples of simulation model are defined below. For instance, Schafer *et al.* (2007) supports community emergency management planning through a geo-collaboration software architecture. It examines geo-spatial maps together and it develops emergency plans and procedures. The software architecture facilitates the development of geo-collaboration solutions. Geo-collaboration tools can be used for emergency management planning. Currion *et al.* (2007) present Sahana Eden, a simulation tool to manage coordination problems faced during an emergency, how to search for missing people, managing aid, and it maintains contacts in the fields of nongovernmental groups, civil society and the victims themselves. Rauschert *et al.* (2002) have a multimodal GIS Interface to Support Emergency Management. In this model the external environment plays a predominant role. With the recent spread of social networks, including in the area of emergency management are trying to develop similar tools. White *et al.* (2009) are studying how social networks can be used for emergency management. The literature presents several simulation models for the management of emergencies based on the behavior and human choices. A cognitive simulation represents the mental processes of the operators during the execution of their duties (1998). The simulation of human action can be qualitative and it represents the evolution of a mental process, or it can be accompanied by calculations and is a quantitative simulation. The output of a qualitative simulation can be a list of actions and errors committed by the operator during work. While in a quantitative simulation there are also the numerical values resulting from the system (Sasou *et al.,* 1995).

Some of the most well-known simulation models are follows:

1. Simulator for Human Error Probability Analysis (SHERPA): It is an integrated simulation model between the HEART method and SPAR-H method. The simulator evaluates the error probability. It can be used both in a preventive phase and in a phase retrospective. It is a quantitative model (Di Pasquale *et al.,* 2015).
2. Probabilistic Cognitive Simulator (PROCOS): It is a model that mimics the behavior of an operator. The model develops a simulator that analyzes the errors. It is a quantitative simulator (Trucco and Leva, 2007).

3. Simulation System for Behavior of an Operating group (SYBORG): The model simulates a group of workers at a nuclear plant. They show some possible combinations of operator errors that can lead to sequences of accidents. The model proposes several strategies to improve collaboration in the group. It is a qualitative simulator (Kirwan, 1998).
4. Cognitive Environment Simulation (CES): It simulates the behavior of a control operator in a nuclear power plant during an emergency situation. The model is developed using artificial intelligence (Woods *et al.*, 1987). It is a semi-qualitative simulator.

3. THE PROPOSED SIMULATION MODEL

The simulation model, presented in this research, aims to identify emergency situations that may occur in different scenarios and quantitatively analyzes the probability of human error during the handling of the emergency phase. The model is divided into several steps, as shown in Figure 1 and as defined follows:

- **Step#1. Activities choice:** It identifies the activities on which simulate the emergency condition, identifying the actions that must make the operator to handle the emergency.
- **Step#2. The emergency situation is simulated at time t.** They identify a number of possible accident scenarios.
- **Step#3. The Generic Tasks (GTTs)** related to the operator's activities are described. Each generic task is defined by a Weibull reliability function that decreases with the increase of working hours. The reliability is maximum in the first hour of work and minimum at the eighth hour of work.
- **Step#4. The nominal error probability** is calculated using the Weibull function related to the generic tasks considered.

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

  This error probability is theoretical and does not take into account the influence of external factors.
- **Step#5. External influences** are inserted into the model through the use of Shaping Performance Indicators (PSF's) (Table 2).

Table 1: Definition of Performance Shape Factors

PSF	Scen. 1	Scen. 2	Scen. n
Decision Time			
Expertise			
Procedure			

The PSF's are indexes that allow you to manage the accident scenarios simulating an improvement or a worsening in the operator's working conditions.

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

- **Step#6.** Finally, by combining the nominal error probability and the values of the PSF's the simulator returns as output the **real error probability**, influenced by the external factors.

$$HEP_{cont} = \frac{HEP_{nom} * PSF_{comp}}{HEP_{nom} * \left(PSF_{comp} - 1\right) + 1}$$

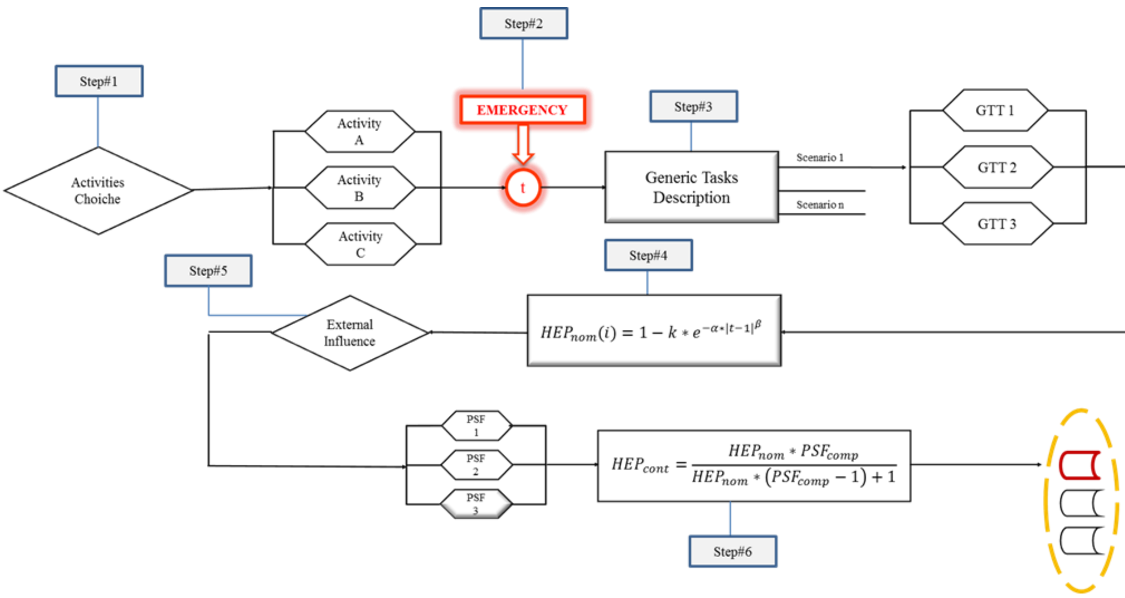

Figure 1: Simulator flowchart

4. THE EXPERIMENTAL SCENARIO

The simulation model replicated the working environment in a way that, overall, is perceived as realistic. The scenario under study analyzed a nuclear power plant. The reason to analyze this specific scenario is because worldwide there are several nuclear plants that could cause high-known risks. Figure 2 shows the map of European nuclear plants. The analyzed scenario aimed to analyze a meltdown occurred at reactor. Figure 3. shows the immersive virtual environment of the Nuclear plant.

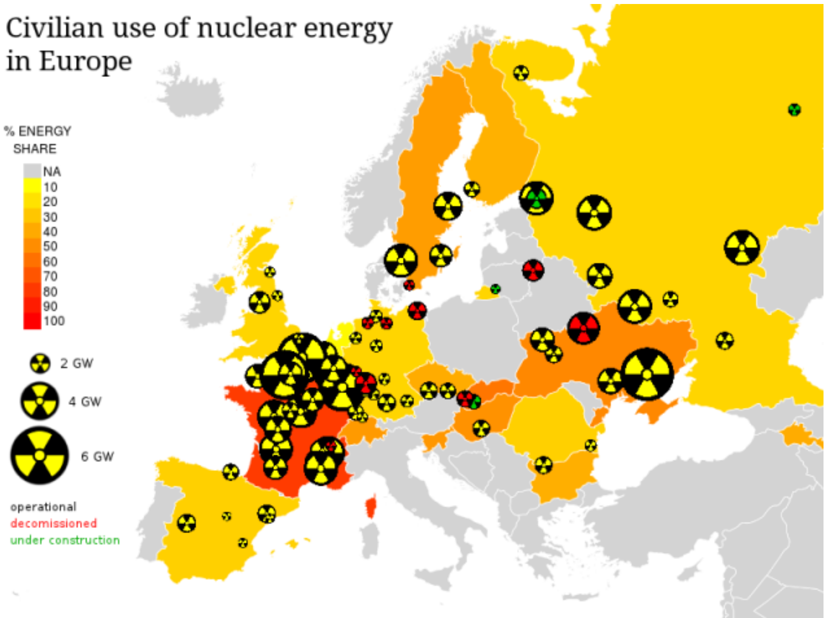

Figure 2: Nuclear energy in Europe, with country colors as nuclear energy share on total energy and symbols representing nuclear power plants with more than one Gigawatt. Source: IAEA - International Atomic Energy Agency

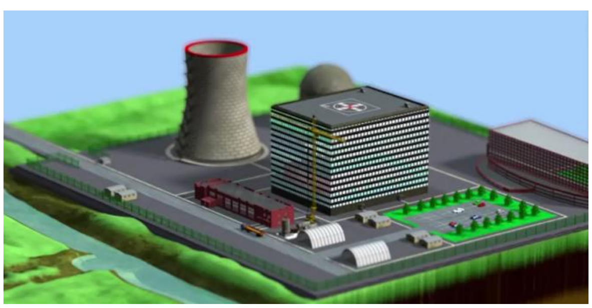

Figure 3: Immersive Virtual Environment of the Nuclear plant

While in Figure 4 is shown a typical replica of a Control Room. A schema of nuclear power plant is shown in Figure 5.

Figure 4: A typical replica of a Control Room

The aim of the nuclear power plant is to produce as much power as possible without causing a meltdown. But it is essential to run the plant up not beyond it's safe operating limits. For this purpose it is important to set plant parameters and to check temperatures and power output day by day. Figure 6 shows and example of parameters setting. However, some problems could accur and cause a meltdown, as shown in Figure 7.

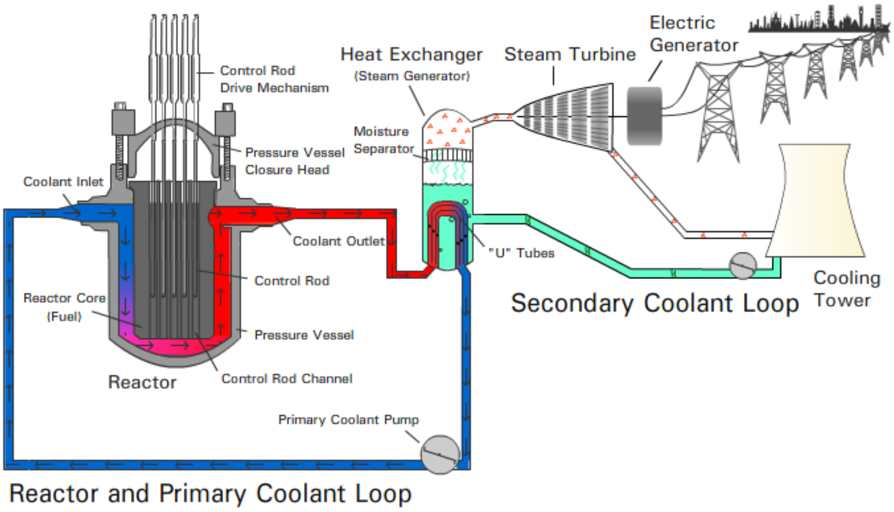

Figure 5: Nuclear power plant – schema

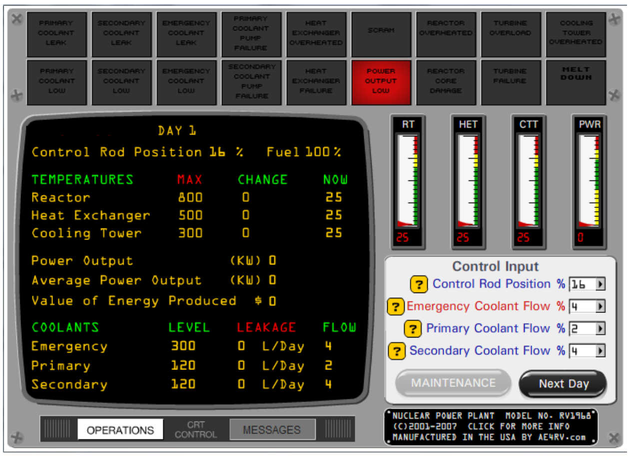

Figure 6: Example of initial parameters

Figure 7: Example of meltdown

The case study is focused on the management of an emergency by operator in the control room, during the meltdown of the reactor in the nuclear power plant.

The operator in the control room, ascertained and understood the magnitude of the emergency activates emergency plan that includes:

- Emergency signal activation;
- Activation cooling system;
- Staff evacuation;
- Alert external rescue system;
- Isolating damaged area;
- Emergency end.

The three simulation scenarios are:

1. **Low Hazard**: occurring while the emergency the decision maker has been monitoring the situation;
2. **Moderate hazard**: the occurrence of the emergency the decision maker can take wrong decisions;
3. **High Hazard:** concerns the decision maker can make a mistake with a good chance.

In the case study is considered the generic tasks in Table 3 that the best represents the operator's activities.

Table 3: Generic Task Analyzed

Generic Task	Limitations of unreability
Routine, highly-practised, rapid task involving relatively low level of skill	0,007-0,045

Considering the three emergency conditions PSF's are defined in Table 4 and the the overall PSF index is calculated for the three condition.

Table 4:Numerically Performance Shape Factors

PSF	Low	Moderate	High
Time	0,01	0,1	1
Expertise	0,1	1	3
Procedure	1	5	20
PSF comp	0,001	0,5	60

5. DISCUSSION AND RESULTS

The results of the simulation of the model defining the nominal error probability and the probability of the contextualized error. (Table 5).

The nominal probability of error is theoretical and it depends only on the considered generic tasks, while the contextualized probability of error depends on the external environment function and it is affected by the PSF values. The simulator returns three different error probability associated with the three different scenarios that can be considered:

- Low Hazard;
- Medium Hazard;
- High Hazard.

As the Table 5 shows the error values are greater for high hazard scenarios.

Table 5: Simulation Results

Generic Task	HEP_{nom} (t)		Low Hazard HEP_{cont}	Medium Hazard HEP_{cont}	High Hazard HEP_{cont}
Routinehighly - practised, rapid task involving relatively low level of skill	t=1	0,007	7,05E-06	3,51E-03	2,97E-01
	t=2	0,009	9,18E-06	4,57E-03	3,55E-01
	t=3	0,012	1,31E-05	6,49E-03	4,39E-01
	t=4	0,017	1,81E-05	8,98E-03	5,21E-01
	t=5	0,023	2,42E-05	1,19E-02	5,92E-01
	t=6	0,030	3,10E-05	1,53E-02	6,51E-01
	t=7	0,037	3,87E-05	1,90E-02	6,99E-01
	t=8	0,045	4,71E-05	2,30E-02	7,39E-01

Figure 8 shows the trend of the PSF as a function of the different scenarios considered.

The performance of the PSF has a fundamental role in the simulation, because it represents the environmental conditions under which the operator must work. Figure 9 shows the result of simulation for the worst case scenario concerning a high risk. The model results are affected by the Weibull reliability function and in fact the reliability of the operator decreases with time, and on the contrary it increases the probability of error. Moreover, the results of the graph are influenced by the working conditions presented with the PSF that worsen the error probability.

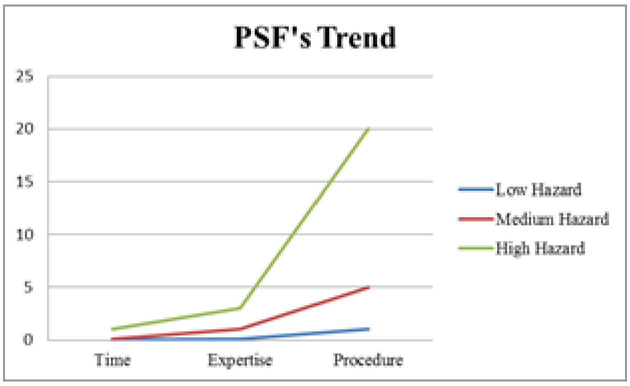

Figure 8: Trend of PSF’s

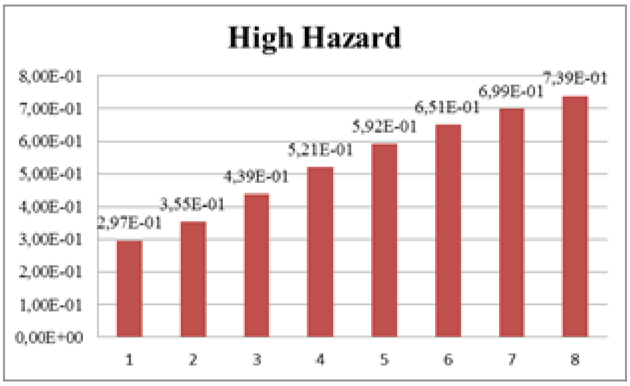

Figure 9: Simulation Results

6. CONCLUSION

Operations of safety–critical systems during emergency conditions, such as the nuclear plant, are certainly difficult to manage. Failing to identify the proper action to do in emergency colud cause high risk. Thus, the proposed simulation model makes it possible to analyze how an action influences critical activity. The proposed approach is semi-probabilistic. Using the model it is possible to take into consideration different contexts by modifying the PSFs involved. A weakness ot the proposed model is that in this early stage does not perform a PSFs time-dependent simulation process. For this reason, future research will consider this kind of dependence.

REFERENCES

Brady, T.F., 2003. Public health: emergency management: capability analysis of critical incident response. In Proceedings of the 35th conference on Winter simulation: driving innovation (pp. 1863-1867). Winter Simulation Conference, December 2003.

Bruzzone, A.G., Frascio, M., Longo, F., Chiurco, A., Zanoni, S., Zavanella, L., Fadda, P., Fancello, G., Falcone, D., De Felice, F., Petrillo, A., Carotenuto, P., 2014. Disaster and emergency management simulation in industrial plants. Proceedings of the International Conference on Modeling and

Applied Simulation (EMSS 2014). September 10-12, Bordeaux, France, pp 649-656.
Cacciabue P.C., 1996. Understanding and modelling man-machine interaction. Nuclear Engineering and Design, 165:351–358.
Cacciabue, P.C., 1998. Modelling and simulation of human behaviour in system control. London. Springer & Verlag.
Currion, P., Silva, C.D., Van de Walle, B., 2007. Open source software for disaster management. Communications of the ACM, 50(3), 61-65.
D'Elia, C., De Felice, F., Mariano, P., Petrillo, A., Ruscino, S., 2013. A bayesian network analysis for safety management, 25th European Modeling and Simulation Symposium, EMSS 2013. Athens; Greece; 25 September 2013 through 27 September 2013; Pages 446-455.
De Felice, F., Petrillo, A., 2011. Methodological Approach for Performing Human Reliability and Error Analysis in Railway Transportation System. International Journal of Engineering and Technology, 3, 341-353.
De Felice, F., Petrillo, A., Zomparelli, F., 2016. A Disaster Risk Management Performance Index to Assess Safety and Security in Industrial Plants. Applied Mechanics & Materials, 84, 373-378.
Di Pasquale, V., Miranda, S., Iannone, R., Riemma, S., 2015. A Simulator for Human Error Probability Analysis (SHERPA). Reliability Engineering & System Safety, 139, 17-32.
French et al., 2009. Human Reliability Analysis: A Review and Critique. Manchester Business School Working Paper.
Hernandez, J.Z., Serrano, J.M., 2001. Knowledge-based models for emergency management systems. Expert Systems with Applications, 20(2), 173-186.
Hollnagel E., 2002. Understanding accidents – from root causes to performance variability. Proceedings of the IEEE 7th Conference on Human Factors and Power Plants, 15-19 September, Scottsdale, Arizona, 2002; 1–6.
Hollnagel E., 2005. Human reliability assessment in context. Nuclear Engineering and Technology, 37(2):159–166.
Kirwan. B., 1998. Human error identification techniques for risk assessment of high risk systems—Part 1: review and evaluation of techniques. Applied Ergonomics. Volume 29, Issue 3, Pages 157-177.
Kuo, Y.H., Rado, O., Lupia, B., Leung, J.M.Y., Graham, C.A., 2016. Improving the efficiency of a hospital emergency department: a simulation study with indirectly imputed service-time distributions. Flexible Services and Manufacturing Journal, 28(1-2), 120-147.
Longo, F., Ören, T., 2008. Supply chain vulnerability and resilience: A state of the art overview. 20th European Modeling and Simulation Symposium, EMSS 2008, pp. 527-533.
Sharit J. Human error and human reliability analysis. In Handbook of Human Factors (4th edn). Salvendy G (ed). John Wiley and Sons, Inc.: Hoboken, New Jersey, 2012; 737.
Ra'ed, M.J., Keating, C.B., 2014. Fragility of oil as a critical infrastructure problem. International Journal of Critical Infrastructure Protection, 7(2), 86-99.
Reznek, M., Smith-Coggins, R., Howard, S., Kiran, K., Harter, P., Krummel, T., 2003. Emergency Medicine Crisis Resource Management (EMCRM): Pilot study of a simulation-based crisis management course for emergency medicine. Academic Emergency Medicine, 10(4), 386-389.
Rauschert, I., Agrawal, P., Sharma, R., Fuhrmann, S., Brewer, I., MacEachren, A., 2002. Designing a human-centered, multimodal GIS interface to support emergency management. In Proceedings of the 10th ACM international symposium on Advances in geographic information systems (pp. 119-124).
Sasou, K.., Takano, K., Yoshimura, S., Haroko, K., Kitamura, M., 1995. Modelling and simulation of operator team behaviour in nuclear power plants. In: Proceedings of the HCI international '95, Tokyo.
Schafer, W.A., Ganoe, C.H., Carrol, J.M., 2007. Supporting community emergency management planning through a geocollaboration software architecture. Computer Supported Cooperative Work (CSCW), 16(4-5), 501-537.
Shannon, R.E., Long, S.S., Buckles, B.P., 1980. Operation research methodologies in industrial engineering: A survey. AIIE Transactions, 12(4), 364-367.
Trucco, P., Leva, M.C., 2007. A probabilistic cognitive simulator for HRA studies (PROCOS). Reliability Engineering & System Safety, 92(8), 1117-1130.
White, C., Plotnick, L., Kushma, J., Hiltz, S.R., Turoff, M., 2009. An online social network for emergency management. International Journal of Emergency Management, 6(3-4), 369-382.
Woods, D.D., Roth, E.M., People, H.E., 1987. Cognitive environment simulation: an artificial intelligence system for human performance assessment. (Technical report NUREG-CR-4862, US Regulatory Commission, Washington DC, US.
Yates, D., Paquette, S., 2011. Emergency knowledge management and social media technologies: A case study of the 2010 Haitian earthquake. International journal of information management, 31(1), 6-13.