HOW HUMAN FACTORS AFFECT THE OUTCOMES OF DISASTERS MANAGEMENT ON INDUSTRIAL SITES

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ABSTRACT

Modeling & Simulation plays a crucial role in the field of Industrial Disaster Management, especially because its outcomes are profoundly affected by human factors. The present research intends to show quantitatively how human behavior affect the outcomes of disasters management on industrial sites. A case study of a fire incident in an Ecuadorian public company engaged in the exploration and extraction of hydrocarbons is proposed. Pareto analysis combined to main effect and interactions effects plots clearly show to the reader how different factors (mostly related to the personnel's behavior and skills, interactions among workers and with the environment) affect the disaster evolutions and its outcomes in terms of loss of human lives, number of injured workers and evacuation times.

Keywords: Simulation, Human Behavior, Human Factors, Industrial Disaster, Emergency Management

1. INTRODUCTION

Most important disasters happened worldwide in industrial plants are characterized by common aspects (e.g. rescue entities involved, emergency management procedures used, etc.). However, the analysis of the disaster type, entities involved and emergency procedures is not enough to understand how a disaster usually evolves over the time and its main effects on the people involved. To this end, the human behavior and the human error must be taken into account. As mentioned by Rosenthal et al. (2001), when a disaster occurs, humans introduce randomness and unpredictability. Randomness and unpredictability introduce, in turn, emergent situations (due to the interactions among the people involved in the disaster and between the people and the external environment) that cannot be predicted and explained a-priori. Such emergent situations may strongly affect the evolution of the disaster over the time in terms of number of injured or death people or evacuation time.

As clearly demonstrated by the current literature, simulation (and specifically Multi Agent Systems, MASs) plays a critical role as tool to recreate the inner complexity of an industrial plant (and workers involved) before and after an emergency situation (e.g. a disaster caused by an explosion and/or fire). Bessis et al. (2011) underlines that MASs have to be regarded (above all when integrated with other methodologies) as next generation technologies for disaster management. By moving in this direction, Hashemipour et al. (2017) propose a framework, based on a Multi-Agent Coordination Simulation System, to be used as a decision-support system to help response manager and operations both for man-made and natural disasters. In addition to general multi agent frameworks and review guidelines about how to use MASs, there are a number of research works proposing specific applications and case studies. For instance, Mat et al. (2017) use a multi agent 3D simulation for flood evacuation, Bruzzone (2013) uses intelligent agent-based simulation for supporting operational planning in country reconstruction after a disaster, while Shi et al. (2009) proposes an agent-based evacuation model of large public buildings under fire conditions.

Therefore, the research effort is moving ahead trying to improve our capacity to understand how emergency scenarios evolve in complex systems (e.g. industrial plants) and to improve our preparedness and responsiveness, even coupling (as already mentioned by Bessis et al., 2011) multiple technologies. To this end, Sugie et al. (2018) develop a disaster prevention system where multi agent simulation is jointly used with robots for evacuation guidance. However, in such an evolving context, it is also worth mentioning that a lot has been done to reduce the probability to have disasters and emergencies. In the industry sectors, modern plants are usually high-automated: this drastically increased productivity whilst reduced the risk of accidents (Woods et al., 2010). The risk of accidents is also reduced by an ad-hoc training of the personnel; from this point of view, the Industry 4.0 and the digital revolution are now giving more emphasis to the importance and effectiveness of simulation based solutions for training (already proved in the past, see for instance Bruzzone and Massei 2010; Beroggi et al., 1995). Currently researches show the Virtual and Immersive Reality and Serious Games can be effectively used to support advanced training in different sectors and application areas (Cohen et al., 2013; Crichton, 2009; Davis et al., 2017).

1.1 Contribution of this article

A survey of the industrial accidents along the last years reveals that, despite the effort to tackle the problem from both sides (from one side better understanding of the emergency evolution and management if a disaster occurs and personnel training, from the other side reduction of the risk of accidents), the ideal condition of zero accidents in the industrial sector is still far to be reached (Twaalfhoven and Kortleven, 2016). Therefore, it is imperative to continue the research efforts in all the directions identified above. To this end, this article propose a multi agent simulation model to investigate the after disaster evolution in an industrial plant. In particular, the authors observe how different factors (mostly related to the workers behaviors and skills, interactions among workers and with the environment) affect the disaster evolutions and its outcomes in terms of loss of human lives, number of injured workers and evacuation times.

The remaining is organized as follows. After a brief description of the industrial site scenario (Section 2), section 3 introduces the multi agent system that has been developed with a focus on the human behavior modeling including human interactions with the external environment. Then, section 4 presents the factors and the performance measures taken into account for the simulation experiments and discusses the simulation results explaining how the chosen factors affect the evolution of the disaster and its outcomes.

2. INDUSTRIAL PLANT SCENARIO DESCRIPTION

Petroamazonas EP is an Ecuadorian public company dedicated to the exploration and production of hydrocarbons. It operates 21 plants, 18 located in the eastern region of Ecuador and three in the coastal zone as shown in Figure 1.

Figure 1. Petroamazonas EP plants

As part of the production process, the oil dispatched at the pumping stations initially passes through a filtering process so that solids contained in the fluid do not affect the different types of equipment it will encounter throughout its journey. Afterwards, if necessary, the oil is heated through heat exchangers (furnaces) in order to reduce its viscosity. Finally, the oil is delivered into centrifugal pumps, which provide the necessary energy so the fluid may be delivered to the next pumping station. These centrifugal pumps operate with internal combustion engines that use crude oil as fuel. For the main engines and pumps to operate properly, it is necessary to have backup systems that perform various functions:

- Air compressors for all instruments;
- Treated fuel (filtered and heated);
- Water for engine cooling;
- Power generators;
- Oil metering systems;
- Oily water drainage and treatment systems, and others.

The plant considered in this paper is the Sansahuari pumping station. The Sansahuari station (Figure 2) is part of the Cuyabeno production system and operates 24/365. Among the main operating systems, we find:

- Oil receiving system;
- Water, gas and oil separation system;
- Oil storage system;
- Water storage system training;
- Re-injection water system;
- Oil pumping system;
- Overheating system;
- Fire system.

Figure 2. Sansahuari Pumping Station

Figure 3 shows the main working points in the plant area.

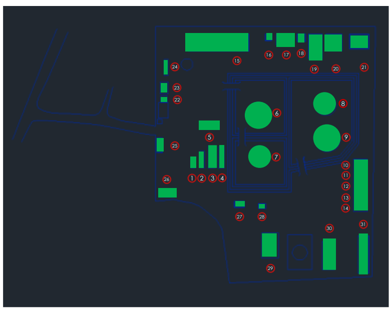

Figure 3. Plant Main Working Points

The main professional figures involved with their duties and responsibilities are summarized below:

- Plant Operators;
- Assistant Plant Operators;
- Chemical Engineers;
- Assistant Chemical Engineers;
- Plant Inspectors;
- Security Operator;
- Maintenance Operator;
- Automation Operator;
- Integrity Operator.

The **Plant Operator** performs all the basic operations and control of the various processes including reception, storage and transfer of petroleum to the central station. He is also in charge of operations synchronization according to the needs of recipients. Therefore, he acts on start-up and shutdown of machines, equipment and facilities while maintaining high levels for safety, quality and environmental conditions. Finally plant operators take care of review of oil production and transfer reports for the preparation of general reports.

The **Assistant Plant Operator** supports the work performed by the plant operator; in particular, control and monitoring of machineries and equipment, production reports and petroleum transfer.

The **Chemical Engineer** takes under control chemical processes during reception, storage and transportation of oil. The Chemical Engineer is also in charge of performing chemical analysis to keep under control the quantities of chemical substances to be injected into the different processes.

The **Assistant Chemical Engineer** supports the work done by the Chemical Engineer, in particular process control and sampling. He also conducts tests under the supervision of the Chemical Engineer.

The **Security Operator** is in charge of controlling public goods for their correct use; he carries out surveillance activities including control of work and safety standards.

The **Maintenance Operator** carries out predictive maintenance on machines and equipment in order to detect anomalies before failures occurences. He coordinates, plans and manages the maintenance activities also executing fault maintenance when needed.

The **Automation Operator** executes preventive and corrective maintenance on instruments including the control of links, interconnections and control loops for rooms and stations.

The **Integrity Operator** executes productive maintenance (non-destructive tests) in facilities and static equipment; he takes under control the distribution of fluids and pressures to ensure the safe operation of the petroleum transfer.

2.1 Emergency Procedures in case of incident

In order to combat unwanted events such as fires, in the operational areas of the Sansahuari station, Fire Systems are available to effectively combat events that may occur within the locations. Figure 4 shows the main coverage of the Plant Fire System.

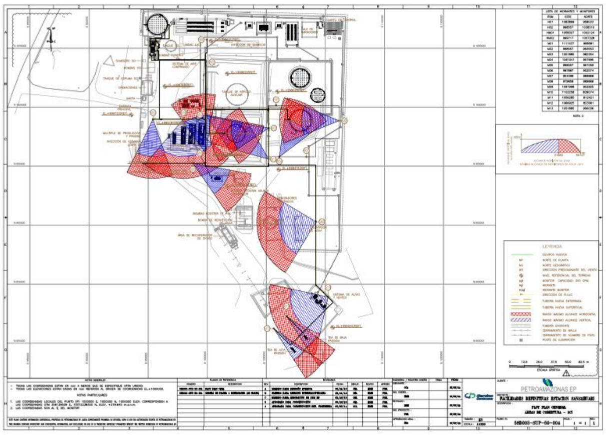

Figure 4. Plant Fire System Coverage

The purpose of the fire emergency response plan is to establish a structured fire control organization at the Sansahuari Station Production Facilities, as well as define roles and functions of firefighters.

The procedure used at the Sansahuari Station for detecting a fire at production facilities is summarized below:

1. The person who detects a fire should immediately notify the Facility Control Room and try to fight the fire only if it has the appropriate resources and if there are minimum safety conditions (fireman's suit, fire extinguisher, PPE, etc.), otherwise it will wait for the arrival of the internal emergency team.
2. The Control Room Operator shall assess the need to activate the Emergency Shutdown System and immediately notify the Operations Supervisor and the Monitoring Center. The person must provide the following information:
    - What is happening;
    - Fire Location;
    - Number of injured (if any).
3. The Plant Supervisor shall immediately notify (in the order given below) the following people to activate the general emergency alarm if necessary:
    - Field Manager;
    - Operations Superintendent;
    - Safety and Security Superintendent;
    - Maintenance Superintendent;
    - Constructions Superintendent.
4. When the general emergency alarm is activated, employees should go to the safety zones while the Rescue and First Aid Team and the internal firefighter team should get ready for starting their emergency management activities. In the meanwhile, the Emergency Manager Coordinator is informed on the magnitude and conditions of the fire, whether or not there is an associated spill and the need to rescue injured personnel.
5. According to the information received, appropriate response activities will start; materials, containment and control equipment will be directed to the

specific site designated by the Emergency Coordinator to start controlling the emergency.

The actions to be performed in the injection area are summarized below:

- Suspend in a safe way the operations that are still running at the time of the event.
- Re-direct the people to the designated meeting points.
- Secure the area.
- Identify the cause of the fire
- Do not enter the fire area without proper personal protective equipment, including self-contained breathing apparatus.
- Disconnect power supplies (close pipe valves, disconnect switch from electrical appliances) near the fire point.
- Identify the area where the fire starts.
- Locate the nearest extinguishers (do not use directly water jets) or fire systems and activate them
- Quickly isolate the area.
- If there are tanks exposed to the fire, use water spray to cool them.

3. HUMAN BEHAVIOR SIMULATION

Multi-agent based systems are particularly suitable for simulating human individual cognitive processes and behaviors in order to explore emergent macro phenomena such as social or collective behaviors. Therefore the authors have developed a multi-agent simulation model to recreate human behavior within an industrial plant in case of emergency.

As part of the simulation model, each human individual is modeled as an autonomous agent who interacts with a 3D Virtual Environment and other agents according to an Individual Behavior Model and some global rules and crowd dynamics rules that derived at the levels of interactions among individuals and group.

3.1 The 3D Virtual Model of the Sansahuari Plant

The purpose of this part is to produce 2D and 3D geometries representing the physical environment of the Sansahuari Plant. Starting from the Sansahuari Plant lay-out, the 2D representation (see Figure 6) and 3D representation (see Figure 6) of the plant has been derived. Elaborating more on the geometries, the 3D models of the most important equipment, machines and components of the plant have been developed.

The 3D Virtual Environment has been also equipped with multiple points of view and the possibility to move around, fly, and observe people behavior during the simulation. A 3D representation of the zone interested by a fire has been also created (see Figure 7) by using Fire Severity Zones circles.

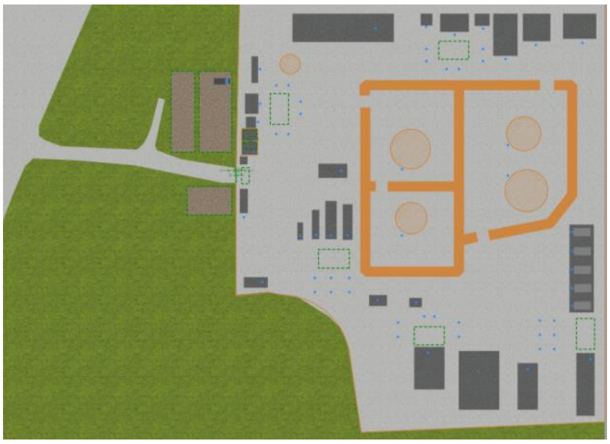

Figure 5. 2D representation of the Sansahuari Plant

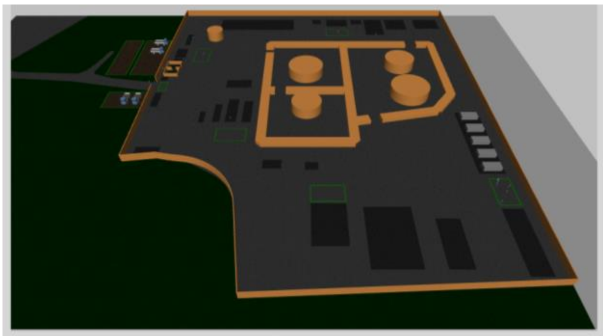

Figure 6. 3D representation of the Sansahuari Plant

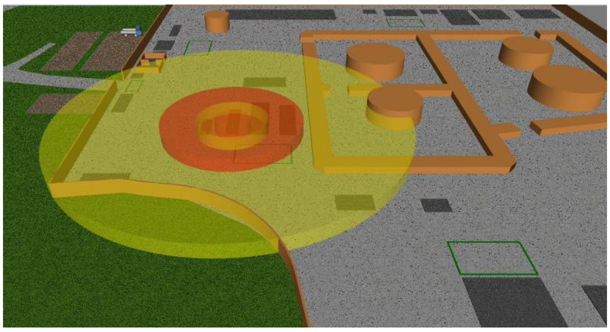

Figure 7. 3D View of the plant and representation of the area interested by the fire

3.2 Personnel Behavior Modeling

According to the information reported in section 2, the personnel working in the plant have their own duties (in the case of normal operations) and should follow specific procedures and action plans in emergency situations. As we have 12 different professional figures working in the plant, 12 different agents have been implemented in the simulation model, each one with its own behavior and designed tasks. Each agent has been programmed individually in order to set-up correctly tasks starting times, executions and durations. In addition, the use of the state charts allow simulating the behavior of the personnel during the emergency, the actions to take, interaction with the environment and the interaction with other people involved in the simulation.

As far as the behavior of the personnel during the emergency is concerned, the following behavior have been implemented as part of the simulation:

- Individual behavior;
- Interaction with the environment;
- Group Behavior.

The individual behavior depends on the position of the person at the time of the event (e.g. at the time of the explosion causing the fire). The assessment of distance determines whether the person is dead, injured or safe according to a Fire Severity Zones circles approach (see Figure 7). The radius values for the death zone, injured zone and safe zone depend on the explosion and fire type; this variables have been set-up as parameters of the simulation model (to give the user the possibility to simulate multiple scenarios and carrying out what if analysis).

Once the distances are determined and evaluated for each person, the evacuation process begins. As far as the behavior of the personnel during the evacuation is concerned, two major approach have been used:

- a Queueing Behavior: people go to the safety zones in an orderly manner respecting distances, speeds and security actions
- a Competitive Behavior: people try to leave as soon as possible without respecting safety standards, this is due to the high stress, fear and instinct of survival present in each person. The effect produced by the Competitive Behavior is known "faster is slower effect", the faster a person wants to go, the slower will be the entire process due to phenomena like clogging, impatience, etc. (Helbing et al., 2000).

It is worth mentioning that the situation evolves dynamically during the simulation; therefore during the evacuation, additional emergency situations are randomly generated (e.g. a new explosion and a new fire). This will affect again the people states (e.g. number of dead or injured people) and the evacuation process.

4. SIMULATION EXPERIMENTS AND RESULTS

The simulation model presented in the previous section has been used to carry out experimentations to determine how certain factors affect the evolution of the emergency situation in the plant and the evacuation.

4.1 Main Factors considered in the experimentations

The factors taken into account are described below:

- Task familiarity (A)
- Crowd Behavior (B)
- Human Error Mode (C)
- Fire Severity Zones circles Radius (D)
- Incident Gravity and secondary effects (E)

Task familiarity: it is the familiarity level with the task being performed by the operator. This task may assume two different levels:

- Totally unfamiliar (0), when the plant operator has no knowledge about the task that he executes; this condition arises when the operator does not receive the initial training therefore he does not have the necessary knowledge to perform the assigned task.
- Routine, highly-practiced (1), when the plant operator is knowledgeable about the task he executes, he is well-trained and he has all the necessary knowledge to perform the assigned task.

Crowd Behavior: it determines the behavior of people during the evacuation process. As mentioned in section 3.1, we have two different crowd behaviors: Queueing (0) and Competitive (1).

Human Error Mode: this factor expresses operator's degree of concentration while performing the assigned task. It is assumed that the factor may have two levels: average-low (0) and average-high (1) degree of concentration.

Fire Severity Zones circles Radius: this parameter indicates the dimensions of the incidence radius according to the explosion type. Also in this case it is assumed that the factor may have two levels: low radius (0) between 20 and 30 meters; great radius (1) between 50 and 60 meters.

Incident Gravity and secondary effects: these parameters expresses the gravity of the incident and the probability to have additional side effects (e.g. secondary explosions/incidents). The factors has two different level: (0) it means low gravity incident with low probability of generating additional incidents and side effects; (1) it means high gravity incident with high probability of generating additional incidents and side effects.

4.2 Performance measures considered in the experimentations

A set of performance measures have been taken into account to understand how the previous described factors may affect the evolution of the emergency situation in the plant and the personnel evacuation. Namely, the following performance measures have been considered:

- Number of workers death.
- Number of workers injured.
- Number of non-injured workers.
- Number of errors that the operator commits due to its low concentration.
- The evacuation time, is considered the time in which an explosion occurs and the time that elapses until the last person arrives in the safety zone.
- The frequency of the evacuation time during the simulation time.

4.3 Simulation results and discussion

A sensitivity analysis has been carried out by considering the effects of the five factors on each performance measure. Figure 8 shows a Pareto Analysis for the number of workers death. The Pareto analysis reveals that the most relevant factors affecting the number of workers death are primarily the Incident

Gravity and the Fire Severity Zones circles Radius. While the dominant effects of factor E and D were expected, it is worth highlighting that there are second order as well as fourth order interactions that play an important role, namely:

- the interaction between the task familiarity and the crowd behavior;
- the interaction between the Human Error Mode and the Fire Severity Zones circles Radius
- the interaction between the Crowd Behavior and the Incident Gravity
- two fourth order interactions involving almost all the factors.

The second order interactions well explain how the number of workers death is jointly related to the operator experience but, during the evacuation, the number of workers death can be increased by a competitive behavior. Furthermore, the number of workers death decreases when the workers operate with higher degree of concentration but the decrease rate is smaller in case of larger Fire Severity Zone circles radius. Finally, the number of workers death increases when the Incident Gravity is larger, but the increase rate is even smaller when the evacuation happens according to a queueing behavior. As far as the fourth order interactions are concerned, these are quite difficult to explain and can be regarded as emergent situations due to the workers behavior, attitude and process and environmental factors.

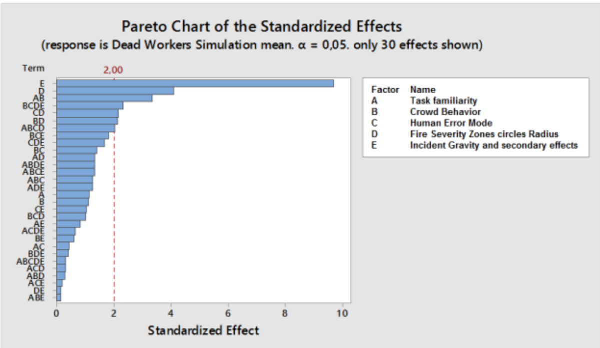

Figure 8. Pareto Chart Analysis for the number of workers death

Figure 9 shows the main effect plots for the Fire Severity Zones circle Radius and for the Incident Gravity factors. The percentage of workers death increase with the increase of the radius and decreases with the decrease of the incident gravity.

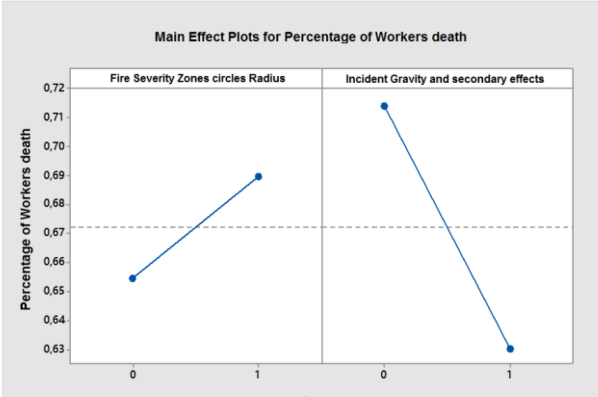

Figure 9. Main Effect Plots for the Percentage of workers death

Similar results have been obtained for the other performance measures. Figure 10 shows the Pareto Chart for the number of Injured people. Also in this case, several first order effects and higher order interactions can be observed. Figure 11 shows the Main Effect Plots for the percentage of injured workers as function of the three most significant factors.

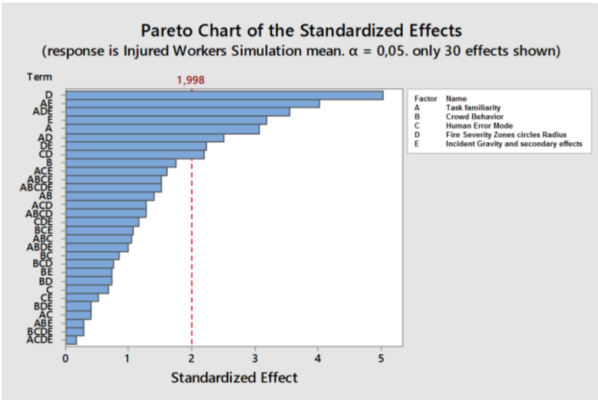

Figure 10. Pareto Chart Analysis for the number of workers injured

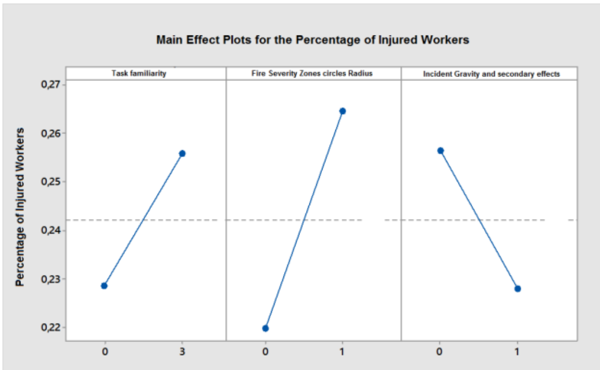

Figure 11. Main Effect Plots for the Percentage of injured workers

Finally, Figure 12 shows the Pareto Chart for the Evacuation time where it is possible to observe that there are multiple main effects and higher order interactions. While this result demonstrates that there are emergent situations that cannot be easily explained (e.g. having a significant fifth order interaction among all the factors considered) it also confirms that the simulation model is able to take into account correctly (from a logical point of view) how different factors may affect the evolution of a disaster in an industrial plant (e.g. the crowd behavior, the gravity and extension of the disaster, etc.).

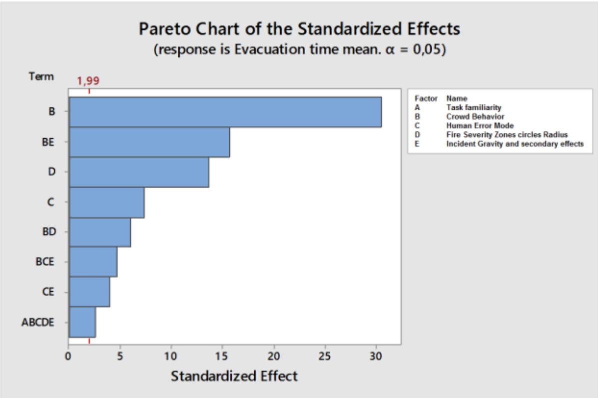

Figure 12. Pareto Chart Analysis for the Evacuation Time

5. CONCLUSIONS

The paper presents the results of a research work in which the main focus was the investigation of how the human behavior may affect the evolution of a disaster within an industrial plant. To this end the authors have developed an agent based simulation model including specific behavior models for agents (before and after the emergency, e.g. an explosion and a subsequent fire). The simulation model has been developed selecting as case study a real industrial plant (the Sansahuari Pumping Station) located in Ecuador. The simulation model has been used to carry out experimentations evaluating how different factors (related to workers capability and skills, workers behaviors, type of emergency/disaster) affect a set of performance measures (related to the disaster evolution such as number of workers injured and death, evacuation time, etc.). Simulation results shows both that the simulation model is able to recreate correctly the emergency evolution over the time (and the effects of the most relevant factors) and that there are some emergent situations (interactions among different factors) that cannot be easily explained (mostly due to the behavior of the different agents in the simulation and the interactions among them and with the environment).

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