A COMBINED APPROACH FOR EMERGENCY MANAGEMENT USING AHP AND SYSTEM DYNAMICS

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ABSTRACT
Emergency management plays a critical role in industrial plants design and management. The investigation of all the entities involved and the possible factors, which intervene during an emergency, can determine the safety of human life and the security of assets. In this article, the authors use the AHP method to derive a ranking of factors which affect both the development of the emergency events and the various entities involved in the disaster. The AHP ranking is then used by a system dynamics model that reproduces an emergency scenario that takes into account all the variables and the entities involved. By performing several experiments, the system dynamics model shows that the emergency management is strongly affected by the parameters considered by AHP. Therefore, having identified the key factors, it's possible to act on them to achieve better management of resources, the least number of victims and the best assets protection.

Keywords: Industrial Plants, System Dynamics, AHP, Emergency management.

1. INTRODUCTION

The security and emergency management is a critical aspect of every activity or process. This is even more important in industrial plants, where security and emergency management has gained an increasingly importance in time. An industrial plant manages technological resources but also human resources and the main target is to secure their safety and integrity (Kuwata et al. 2004). The security management aims to prevent any incidents which may result in undesirable effects on people inside or outside the site, the environment or on company resources. If despite all prevention efforts, an emergency happens then an effective emergency management is the only way to tackle successfully the problem.

In industrial plants, a high level of security grants a correct management of assets during their life cycle. Indeed, security already starts during the assets design phase, by applying the technical and precautionary standards, then different types of maintenance and control assure the assets security over the time (Longo et al. 2012). Furthermore, emergency plans aim at planning one or more sequences of actions to minimize the consequences in case of accidents.

Research & Development activities in the area of emergency management usually involve:

- the identification and assessment of possible accident scenarios and their effects through the use of complex mathematical models;
- planning and emergency management (operational procedures, suitable tools and dedicated infrastructure);
- solutions for training and exercises.

In the end, emergency management in industrial plants is definitely a complex issue, characterized by many stochastic variables (eg. response time, availability of resources, evolution of the disaster scenario, etc.). These variables interact with each other and increase, as the time goes by, the complexity of the system (Bruzzone et al. 2014). Often, the use of analytical models to support the proper management of emergencies does not guarantee reliable results. In fact, the analytical methods require simplifying assumptions that may affect the trustworthiness of the results themselves (Banks 1998). Consider as an example the transportation of the injured people from the disaster site to the hospitals and the nearest first aid facilities. A number of variable including the type of road, traffic and weather conditions, type of vehicles, etc., should be properly considered (Bruzzone et al., 2006) both to support the emergency management and, in an early phase, the road network design and facilities locations. In that context, it is therefore essential to be able to recreate the complexity of the real-world system

(Bruzzone et al., 2007). System Dynamics is surely a reliable method and also a possible way to study the problem, especially if we are dealing with very complex situations or have many processes, many stochastic variables and questions that are difficult to give an answer (Taboada, 2011). Furthermore, the Analytic Hierarchy Process (AHP) proposed by Saaty (1980) is a widely used method and has been applied in a large variety of areas including planning, selecting a best alternative, resource allocation and conflicts resolution (Nachiappan et al., 2012). For example these are some application of AHP in specific fields: research and development (R&D) projects selection, marketing (Wind et al. 1980, Mark 2001), medical and healthcare decision making (Liberatore et al. 2008), resources allocation (Heidenberger 1999), energy (Pohekar 2004) and process safety (Arslan 2009). AHP has also been integrated with other techniques, e.g. SWOT, meta-heuristics, etc., (Ho 2008). This article proposes the application of AHP and system dynamics for supporting the understanding of emergency management in industrial plants. The proposed approach combines AHP and System Dynamics for organizing and analyzing complex decisions and understanding the nonlinear behavior of complex systems over time. Indeed, the System Dynamics model intends to test various configurations of emergency management for different scenarios while taking into account the AHP output.

The article is organized as follows: section 2 presents the emergency scenario; section 3 describes the System Dynamic model; section 4 explains the AHP model. Sections 5 and 6 summarize main results and conclusions.

2. EMERGENCY SCENARIO DESCRIPTION

This section presents a general disaster scenario which will be duly declined on a specific case (as described later in the paper) through a system dynamics model.

In particular, it has been hypothesized an explosion in an industrial plant devoted to store petrochemical products. The event affects a certain percentage of the industrial plant area and it is assumed the presence of a certain number of not evacuated employees.

Preliminary information on injured people in the disaster are also available according to a triage approach based on green, yellow, red and black codes.

Some of the evacuated employees are part of the internal emergency team. The internal emergency team usually intervenes with proper devices (according to the received training) helping in evacuation procedures, operative procedure (e.g. release valves and electrical systems, etc.) and recognition (with external aid).

In this general scenario, we also hypothesize the presence of an hospital (close to the industrial plant); in particular it is known the distance between the hospital and the place of the disaster, the type of connection roads and the number of available resources (e.g. ambulances).

Additional scenario information regard the number of tanker trucks, the number of firefighters and where the barracks of the fire brigade is located.

3. THE SYSTEM DYNAMICS MODEL

Systems Dynamics (SD) is an approach for modeling complex and dynamic systems. SD captures an essential feature of many systems: the capability of self-regulating over time (Collins el al. 2013). This means that feedbacks among the system components incrementally adjust the state of the system.

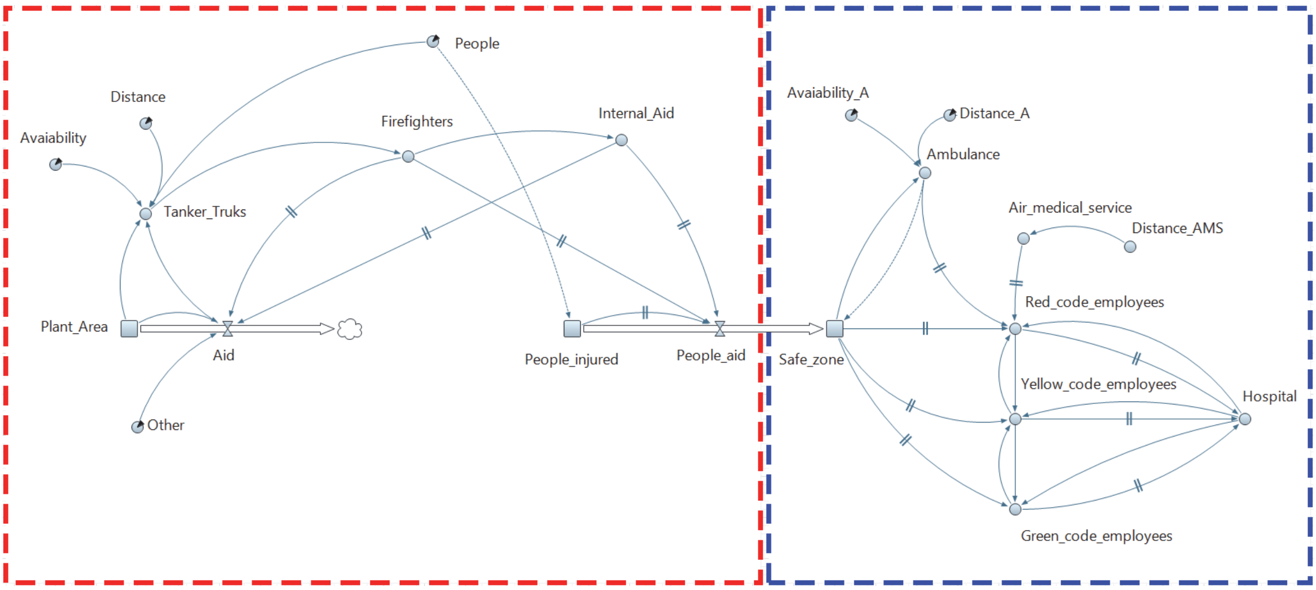

Figure 1 – Causal loop diagram of an emergency management system. The diagram discerns the complexity of the system into the major variables and feedback loops of emergency management.

A change in one part of the system affects another part that, in turn, may affect others with some delay, some of these changes will eventually feedback to amplify or dampen the effect of the original change.
In short, an SD model recognizes that changes do not occur in isolation and furthermore that many systems do not respond instantaneously to these changes. SD represents the interactions between the elements of the system through causal loops (see figure 1). SD takes an approach to analyze the impacts of complex dynamic interactions in a system. (Forrester, 1961).

3.1. Fire management model

Figure 1 is a casual loop diagram that represents the dynamics impacting an industrial fire management system.
The box on the left part of the figure represents the fire itself, the factors that affect its expansion and how this is handled. The right box represents how the assistance of the ambulance is managed. Starting from the left box, we identify the fire level that, together with rescue operations are the key variables that connect the fire department and the internal emergency team to the one that is the ultimate goal of the model: extinguish the fire.
The distance of the fire department from the emergency area and the number of tanker trucks can be included in the model as well but they do not affect directly on the fire evolution. Indeed, the performance indicators taken into account in this study are not the time to extinguish the fire or the time needed to transport the victims to the nearest hospitals (according to the types of injuries) but, more appropriately, the percentage change of these times in correspondence of the variation of the main parameters.
The parameters that can be modified in the SD model are the same that have been taken into account in the AHP and are those that affect the final output. Behavioral and operational procedures that mark the various moments of the emergency cover different aspects as briefly explained below.

3.2. Fire parameters

The first aid role is given to the internal emergency team. The team has the following duties:

- Immediate intervention after the fire explosion;
- deal with the timely rescue of potential victims by implementing, if necessary, preparation maneuvers to make it accessible to rescuers;
- inform the firefighters.

Once received the alarm, the Fire Department will intervene with operational teams whose number, in terms of tanker trucks and firefighters, will depend on the severity of the fire. The influence that firefighters may have on the fire depends on the following parameters:

- distance of the fire department from the place of emergency;
- time between the request for assistance and the arrival of the rescue teams;
- number of units sent by the command.

The Firefighters are responsible for:

- fire extinguishing
- ensure the conditions for a quick and safe rescue of the workers from the fire area to the safe zone.

3.3. Rescue parameters

As it can be seen from the right box in figure 1, the emergency management, starting from the safe zone, depends by:

- the number of people involved in the fire;
- the arrival time of ambulances;
- the number of available ambulances;
- the hospital distance from the place of emergency;
- the presence of the air medical service and its distance from the fire location;
- the transfer time to the hospital of people injured.

The ambulances arrival in the safe zone will determine the division of the injured people according to the gravity of their situation: red code, yellow code and green code.
The dwelling time of the injured in the safe zone depends on their code. As far as the hospital transportation is concerned, priority will be given to the red codes, to be followed by the yellow and finally to the green codes.
Starting from the original scenario there are several decisions to be taken as well as there are different factors that will affect the fire extinguishing time and the time required to perform injured people transportation to the nearest hospitals. Obviously, based on these decisions it is possible to act in a more or less significant way trying to manage as well as possible the entire emergency.

4. THE AHP MODEL

The AHP is a decision-making procedure originally developed by Saaty in the 1970s. First of all, it is important to know the environment in which the industrial plant operates. This basically means the understanding of the the external environment and of the internal company organization. The analysis is undertaken with the aim of

- establishing the strategic, organizational and risk management;
- identifying the constraints and opportunities of the operating environment.

In this paper the AHP methodology is used to rank alternatives factors that influence in different way the emergency management evolution through the use of different criteria.
In an emergency management, the factors that come into play are countless and each one influence in different ways the various phases and the different

entities involved in it. Considering the scenario described in the previous section, we found the following entities part of the emergency management:

- Ambulance;
- Non-transporting EMS Vehicle;
- Air Medical Service;
- Doctor;
- Tanker Truck;
- Fire Fighters;
- Patrol.

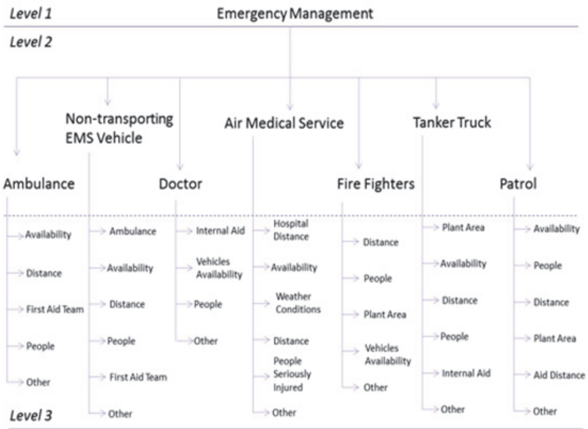

Figure 2 – AHP network

For each entity the following criteria have been found (see also figure 2):

- *Availability* (A) – entities number available nearby the disaster;
- *Distance* (D) – the distance between the disaster site and the entities ;
- *People* (P) – number of people involved in the disaster;
- *Plant Area* (PA) – area (in m^2) concerned in the disaster ;
- *First Aid Team* (FA) – tells if the first aid team could intervene before the external aid arrivals on the disaster site;
- *Other* (O) – other criteria not much relevant on the entity are expressed here.

Once defined the criteria, seven related matrices and the resulting weight vectors have been generated. In order to streamline the text, only the matrices related to Tanker Truck and Ambulance are shown in the following tables.

Table 1- AHP Tanker Truck

	P	A	PA	IE	D	O	W
P	1	0.5	0.5	2	0.33	3	*12.42%*
A	2	1	1	3	2	5	*27.40%*
PA	2	1	1	3	1	5	*23.95%*
IE	0.5	0.33	0.33	1	0.25	2	*7.63%*
D	3	0.5	1	4	1	4	*23.88%*
O	0.33	0.2	0.2	0.5	0.25	1	*4.71%*

According to AHP method, a Consistency Ratio CR is calculated for each matrices:

$$CR_{amb} = 9\% \quad (1)$$

$$CR_{tt} = 2\% \quad (2)$$

Table 2- AHP Ambulance

	A	D	P	O	FA	W
A	1	0.33	0.2	6	1	*13.09%*
D	3	1	0.33	5	3	*23.41%*
P	5	3	1	5	7	*49.23%*
O	0.17	0.2	0.2	1	0.33	*4.83%*
FA	1	0.33	0.14	3	1	*9.44%*

The CR tells the decision maker how consistent he has been when making the pair-wise comparisons. It is necessary that the CR is less than 10% to consider the decision maker consistent. Consequently, using as reference the AHP Ambulance table, the weight vector (W) ranks the criteria according to their importance:

1. People;
2. Distance;
3. Availability;
4. First Aid Team;
5. Other.

That means the People parameter is the most influent so its variation creates a notable change in the entity. Obviously, a variation in the Distance parameter will be more influencing than a variation of the Availability and less influencing than the People parameter.
Similar rankings have been found for the Tanker Truck as well as for the Non-transporting EMS Vehicle, the Air Medical Service, etc.

5. EXPERIMENTS AND RESULTS

This section reports some preliminary experiments that have been carried out by using the system dynamics model according to the AHP rankings. Such experiments allows to:

- deepen the relationship between the fundamental variables involved in the management of the entire emergency (namely the methods used in extinguishing the fire and the resources used for injured people transportation to hospitals) and the factors associated with these variables that, with different weights, will influence the results in terms of emergency management;
- testing and validate, for each variable, the hierarchy of values resulting from the AHP analysis.

The results in terms of emergency management are calculated according to two performance measures:

- Time taken to extinguish the fire;
- Time needed to transport the injured to hospitals.

As case study, it has been assumed to properly decline the scenario defined in section 2. The factors were chosen to ensure e a certain plausibility in the overall management of the disaster. The parameters values are shown in figure 3 as they appear in the System Dynamics model interface. To this end, please note the System Dynamics model has been opportunely equipped with a Graphic Interface that allows the user declining the general disaster "picture" described in section 2 and therefore carrying out a experiments on a number of different scenarios.

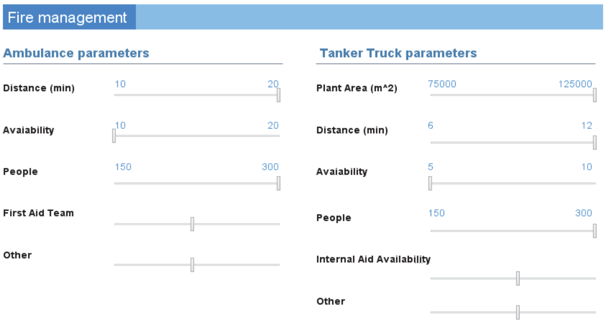

Figure 3 – Starting Scenario

It is worth saying that the time to extinguish the fire is directly connected to the tanker truck variable, while the time required to transport the injured people to the hospitals is connected to the ambulance variable. In particular, as noted in section 3, it is important to understand to which extent a variation of a specific factor may influence the performance measures.
Furthermore, to check the validity of the ranking given by the AHP four different configurations were tested (for the scenario depicted in figure 3) and the results are reported in table 3.

Table 3- Scenarios analyzed

Ambulance	Scenario	Scenario1	Scenario2	Scenario3	Scenario4
Distance	20min	-	10min	-	-
Availability	10	20	-	-	-
People	300	-	-	150	-
First Aid Team	-	-	-	-	-
Other	-	-	-	-	-
Transportation Time		49%	50%	51%	1%
Tanker Truck					
Plant Area	125000m^2	-	-	-	75000m^2
Availability	5	10	-	-	-
Distance	12min	-	6min	-	-
Internal Aid Availability	-	-	-	-	-
People	300	-	-	150	-
Other	-	-	-	-	-
Fire Extinguishing Time		49%	9%	1%	44%

The analysis of the results reported in table 3 establishes that the variation of a factor significantly affects (with a certain weight) the performance measures. Taking into account the ambulance variable it can observed for example how, in Scenario 3, the factor "people involved" may strongly affect the time required to transport people to the hospitals (51% reduction). Similarly, the Ambulance availability and distance may tremendously impact the time needed to transport injured people to the nearest hospitals. The analysis of the lower part of table 3 reveals that tuck tankers availability and the extension of the industrial plant area may significantly affect the time fire extinguishing time. Similar results have been obtained by considering other variables; furthermore, the results shown in table 3 confirm the rankings obtained by the AHP model where the factors people, distance and availability are the most critical to tackle correctly the emergency management.

6. CONCLUSIONS

Over the years, the accidents occurred in industrial plants have led to disastrous consequences both for the number of victims, the damage to assets and for the surrounding environment, so correct approaches to emergency management are needed. The approach proposed in this paper shows that the integration between two different methodologies (namely AHP and System Dynamics) may produce significant advantages in understanding how the different factors involved in the emergency management may influence some critical performance measure. In particular, the outputs obtained from the AHP model can be validated by suing the System Dynamics model. Furthermore, the System Dynamics model provides the user with the possibility to analyze a large set of potential disaster scenarios. To this end, the model itself is based on a general disaster "picture" that can be declined (or customized) by the user according to the specific need. The system dynamics model can be used to investigate scenarios where multiple people are involved and few resources are available or scenarios where large industrial plants are located in external city areas and therefore far from firefighters and hospitals, etc.
Understanding the key factors of a disaster can provide several hints to identify the best place to locate resources as well as industrial facilities (above all in areas considered at risk) as well as to define new rules and procedures to improve emergency management.

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