A MULTIDISCIPLINARY SIMULATION TOOL FOR HEALTHCARE EMERGENCY MANAGEMENT

De Felice, F.[(a)], Petrillo, A.[(b)], Frascio, M.[(c)], Mandolfino, F.[(d)], Zomparelli, F.[(e)], Esposito M.[(f)]

[(a),(e),] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Via G. di Biasio 43, 030434 – Cassino (FR) – Italy
[(b)] Department of Engineering, University of Naples “Parthenope”, Centro Direzionale, Isola C4 80143 – Napoli (NA) – Italy
[(c),(d)] Department of Surgical Sciences and Integrated Diagnostic, University of Genova, Largo R. Benzi 8, 16132 – Genova (GE) – Italy
[(f)]ABC Via Argine, 929, 80147 – Napoli - Italy

[(a)]defelice@unicas.it,[(b)]antonella.petrillo@uniparthenope.it, [(c)]mfrascio@unige.it,
[(d)] fcmandolfino@gmail.com, [(e)]f.zomparelli@unicas.it, marcovik@libero.it

ABSTRACT
The aim of this research is to propose a multidisciplinary and integrated solution for healthcare system analysis. The specific goal of the simulation model is the development of an analytical algorithm to support healthcare rescuers to define how to make optimal choices in the face of risk (or uncertainty). The methodological approach integrates three aspects: 1) triage algorithm, to assess patients’ condition 2) multi-criteria analysis, to define a ranking of hospitals and 3) emergency simulation. Medical staff, through the mathematical application of the triage algorithm, assesses patients’ condition by assigning them a severity code. Then, through a multi-criteria approach a ranking of hospitals is defined. Thus, the decision maker can easily find the most suitable hospital where transfer patient. Finally, the model is simulated through Flexsim Software©. The research tries to overcome the qualitative evaluation that characterize the traditional healthcare models. The model is implemented in a real case study concerning an emergency scenario in a petrochemical plant.

Keywords: Emergency management, Emergency simulation, triage, decision making

1. INTRODUCTION

In recent years the focus about operators’ health and safety is growing. With technological innovation, industrial plants have become increasingly complex and the accident management inside them is always more difficult. The literature analysis shows that publications on issues of emergency management during an industrial disaster are growing (De Felice *et al.*, 201 a). Emergency management is a very complex process, which involve many different actors (Bruzzone *et al.*, 2015). One of the main aspects of emergency management is the healthcare process (Christian *et al.*, 2006). During a disaster it is necessary to develop a healthcare plan to protect operators’ safety. Healthcare process during an emergency is based on two fundamental aspects: 1) patients’ severity evaluation and 2) choice of hospital where patients have to be cured. These two activities require the human decisions. Unfortunately, during emergencies, the human reliability decreases, because it increases the human error probability (De Felice *et al.*, 2016 b). It is necessary to develop an analytical and objective model to help the decision maker during emergency conditions and to reduce human errors. Literature review highlights that the most healthcare emergency models are strongly related to subjective decisions of operator (Considine *et al.*, 2007). The goal of the present research is to develop a healthcare integrated model to manage emergency conditions. The research integrates different traditional systems to develop an analytical – mathematical model for healthcare emergency management. In detail, the paper presents a new emergency triage model, which allows to identify and assess patients’ conditions in a few minutes, using a mathematical algorithm. In addition the research proposes a multi-criteria approach, based on Analytic Hierarchy Process (AHP), developed by Saaty (1977), to define a ranking of hospitals in which to lead patients. The proposed model is implemented in a real case study to test healthcare management during an emergency condition. Finally, it is worthy to note that the model is simulated through Flexsim 2017 software. Outcomes drive the actions of medical staff to provide the best care for a patient. The present research overcomes literature limitations about the traditional models of healthcare management, defining a new mathematical tool for emergency healthcare analysis and simulation. The rest of the paper is organized as follows. Section 2 presents a literature review on triage emergency model. Section 3 describes the proposed methodological approach. Section 4 describes the emergency scenario under study. Finally, in section 5, conclusions are analyzed.

2. LITERATURE REVIEW

Literature on triage models is very rich, because aspects of human healthcare have a key role during an emergency management. Following, some of best known triage models are presented. Canadian triage and acuity scale (CTAS) is a triage model developed in the 1990 in Canada (Warren *et al.*, 2008). CTAS uses a list of clinical symptoms to assess the triage level (Murray, 2003). It defines a scale with five levels:

- Resuscitation: patient has a heart attack and he risks his life;
- Emergent: patient is seriously injured;
- Urgent: patient's condition may worsen;
- Less urgent: patient has no serious injuries;
- Non urgent: patient's condition is not pejorative.

Australasian triage scale (ATS) is a triage model developed in the 1994 in Australia. All patients should be assessed by a doctor who analyzes patient's conditions (Considine *et al.*, 2004). ATS model provides five levels of severity (Table 1).

Table 1: ATS levels

ATS Triage Scale	
Category	Category description
1	Immediately life-threatening
2	Imminently life-threatening
3	Potentially life-threatening
4	Potentially serious or urgency situation
5	Less urgent

Manchester triage system (MTS) was developed in Great Britain. It has a five level scale (Roukema et al., 2006). MTS uses 52 diagrams which represent patient's symptoms. Diagrams allow to evaluate patient's conditions. When a patient shows symptoms, the doctor examines his situation and he determines the treatment priority according to the triage scale (Grouse et al., 2009). Emergency severity index (ESI) is a triage algorithm developed in the USA in the late 1990 (Eitel *et al.*, 2003). Triage levels depend on the patient's severity and necessary resources. ESI model is based on four points decision. They reduced to four key questions:

1. Does this patient require immediate life-saving intervention?
2. Is this a patient who shouldn't wait?
3. How many resources will this patient need?
4. What are the patient's vital signs?

The answer to these questions defines five levels of triage model assessment (Platts Mills *et al.*, 2010). Simple triage and rapid treatment (START) system is a triage model developed in 1980 in California (Benson *et al.*, 1986). It allows to quickly assess the victims in 15 seconds. After the first evaluation, wounded are visited depth. The model defines four different triage levels (Kahn *et al.*, 2009) (Table 2).

Table 2: START triage scale

START Triage Scale	
Category	Description
	Decesead
	Providing immediate care
	Provide treatment within few hours
	Low gravity

There are national triage models, but also models developed by international organizations such as NATO. Table 3 shows NATO guidelines triage scale (McGrath *et al.*, 2003).

Table 3: NATO triage scale

NATO triage scale	
Category	Description
	Imminent death
	Serious injury
	Potentially serious injury
	Minor injury

Traditional triage models are very qualitative and they do not use mathematical models and numerical algorithms (Robertson, 2006). Patient's analysis is determined by subjective assessment of medical experts. In the literature, there are several mathematical models related to health emergency management. Most of these models are related to patient flow analysis in emergency departments. But literature is lacking in mathematical models of triage evaluation. Coats and Michalis (2001), propose a mathematical modeling of patient flow trough an accident and emergency department. The model constructed was not an accurate representation of patient flow because of the large number of assumptions that had to be made in the preliminary model. De Bruin *et al*. (2007) investigate the bottlenecks in the emergency care chain of cardiac in-patient flow. The primary goal is to determine the optimal bed allocation over the care chain given a maximum number of refused admissions. Another objective is to provide deeper insight in the relation between natural variation in arrivals and length of stay and occupancy rates. Costa *et al.* (2003), propose a mathematical modelling and simulation for planning critical care capacity. The combination of appropriately analysing raw data and detailed mathematical modelling provides a much better method for estimating numbers of required beds.

The developed model allows to define an iterative triage algorithm to assess patient's condition. Also, through a score model it can identify the optimal hospital where cure the patient. AHP has been used in several healthcare studies (Liberatore *et al.*, 2008). For example, Dolan et al., (1993) used AHP to verify the conditions of use of endoscopy. A group of experts formed by 25 patients and 20 doctors, analyzed a five-criteria: cause of bleeding, test complication, cost, length of stay and bleeding. Castro *et al.*, (1996) used AHP to analyze upper abdominal pain. The considered criteria were: cost, discomfort, risk and diagnostic ability. Saaty and Vargas (1998) defined an AHP model to show how can incorporate expert judgment for medical diagnosis. Bahill et al., (1995) used AHP model to define a decision support system to help speech clinicians diagnose children who have begun to stutter.

3. METHODOLOGICAL APPROACH

The proposed healthcare model defines a numerical indicator to assess patient's condition and the best hospital where conduct them. The methodological approach is divided into three different steps as depicted in Figure 1:

- Phase#1: Hybrid triage algorithm for the evaluation of patients;
- Phase#2: Evaluation of hospitals near the accident site, to establish a hospital ranking;
- Phase#3: Emergency simulation.

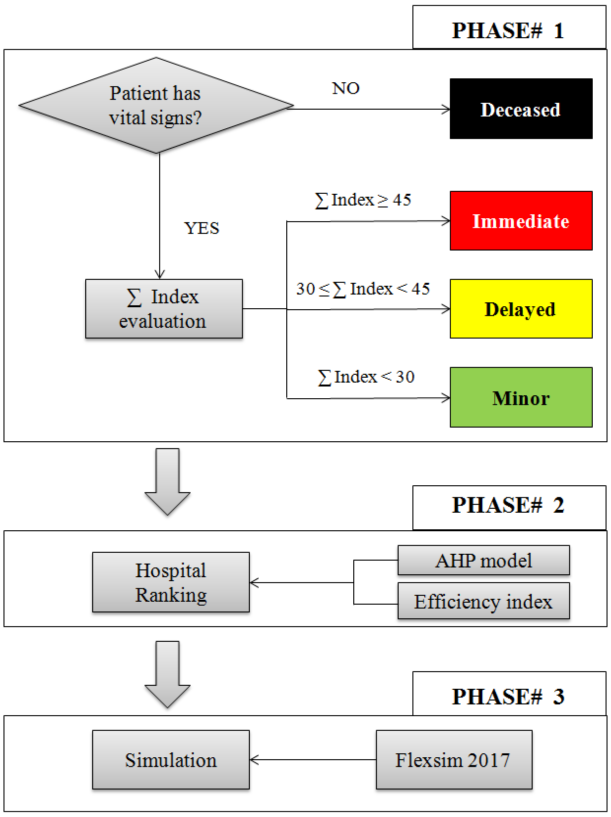

Figure 1: Methodological approach flowchart

In the following sections a description of each phase is provided.

3.1. Phase# 1: Triage hybrid algorithm

Triage hybrid model identifies four levels of emergency. The basic structure of the model is acquired by the START model and the ESI model. But in contrast with these traditional models, triage algorithm combines numerical coefficient to define the patient's level of severity.

Patient's assessment is developed by the health team. Table 4 summarizes triage scale of hybrid algorithm. It describes:

- Level;
- Name
- Time;
- Symptoms.

Table 4: Hybrid triage algorithm scale

Hybrid triage scale			
Level	Name	t (min)	Condition
	Decesead	-	Not survive
	Immediate	10	Very serious
	Delayed	45	Medium serious
	Minor	120	Less serious

For the evaluation of patients the new model involves the use of a quantitative table (Table 5). For each symptom is defined a weight (weights are obtained from the literature analysis). In addition, medical staff visiting the patient defines a value of severity for each symptom. It calculates the index of each symptom with the following formula:

$$Index = Severity \times Weight \qquad (1)$$

Finally the sum of indices defines a total index, which represents the patient's condition.

$$21 \leq \sum index \leq 63 \qquad (2)$$

If a vital function (heart beat, breathing, injury) is absent, patient is evaluated "deceased"
else if:

$$\sum index \geq 45 \qquad (3)$$

patient is evaluated "immediate";
else if:

$$30 \leq \sum index < 45 \qquad (4)$$

patient is evaluated "delayed";
else if:

$$\sum index < 30 \qquad (5)$$

patient is evaluated “minor”.

Table 5: Index triage

Index Triage								
Factors	Severity				Weight			Index
	1	2	3	Absent	0.5	1.5	5	
Level of consciousness						x		
Heart beat							x	
Breathing							x	
Mobility					x			
Panic					x			
Injury							x	
Circulation						x		
Ventilation						x		
Age					x			
								TOT

3.2. Phase# 2: Ranking of hospitals

The model allows to evaluate hospitals to establish an evaluation ranking. The model evaluates hospital conditions trough different criteria. For each criterion, weights and evaluation are defined (Figure 2).

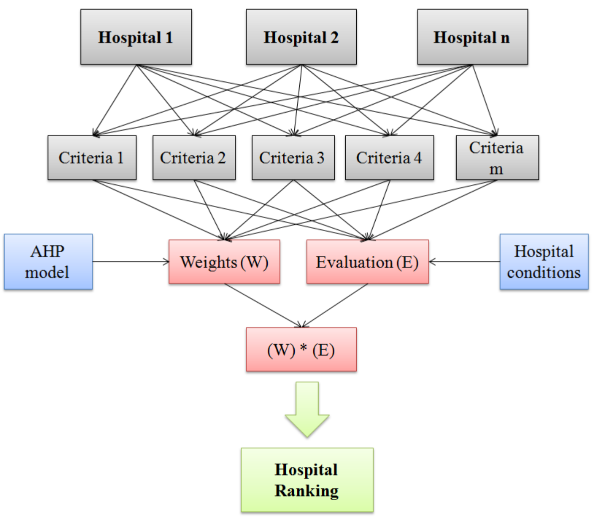

Figure 2: Rating hospitals flowchart

Weights of criteria are identified through AHP. Traditional AHP model is developed through tree level hierarchy. The top level is the main goal of a decision problem, the lower level is the criteria and finally there are alternatives.

In this case, the model only provides for two levels: goal and criteria, which allow to define a criteria ranking. The model is divided into three steps:

- Hierarchy construction;
- Pairwise comparison and relative weight estimation;
- Priority weight vector calculation.

The AHP model defines weights of criteria. After weights ranking, it is possible to assess the evaluation of hospitals (Table 6). The evaluation depends on the hospital conditions. If hospital conditions are good, then the valuation values are high, otherwise they are low.

Table 6: Hospital ranking

Hospital ranking				
Hospital Criteria	Weight criteria (W)	Evaluation (E)		
		Hospital 1	Hospital 2	Hospital n
1	0.30			
2	0.27			
3	0.24			
m	0.19			

For each hospital is calculated the efficiency index (Eindex):

$$Eindex = Weight \ x \ Evaluation \qquad (6)$$

and finally, for each hospital is calculated the overall efficiency index (TOTEindex):

$$TOTEindex = \sum Eindex(criterion) \qquad (7)$$

Hospitals are classified considering the total efficiency index.

3.3. Phase# 3: Simulation

The last step of the model represents the simulation of a healthcare emergency condition in a software environment. Simulation is one of the most used tools for process optimization, because it allows to represent real systems with computer. The importance of simulation is growing in recent years, since it is one of the fundamental pillars of the industry 4.0 revolution. The simulator used in the research is “Flexsim 2017”. It allows to observe the various steps of the emergency management and to analyze interactive dashboard for the evaluation of healthcare performance. Flexsim was chosen because it is a dynamic simulation system that allows to manage deterministic variables, but also probabilistic values, represented through probability distributions. In particular, the speed of ambulances may vary according to traffic conditions, and also the patient's evaluation time may be variable. A probability distribution is used to define these factors in the simulative environment. Figure 3 shows the working simulation software environment.

The simulator was born to model industrial system, but through various customizations it was possible to use it to healthcare simulations.

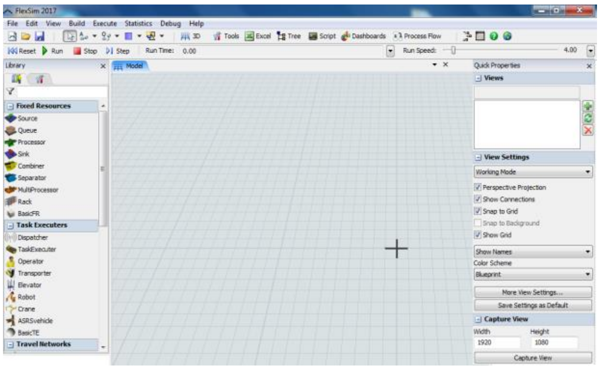

Figure 3: Flexsim working environment

4. EXPERIMENTAL DESIGN: A CASE STUDY

The proposed case study provides a description of an emergency situation in a petrochemical industry. The incident event is the loss of hydrogen sulphide from a tank for the refining used oils. The cause of the accident is a failure of the pumping system that has caused a leak in the fuel tanks. Maintenance workers did not notice the problem that was degenerated causing an emergency condition. After, the alarm is triggered, all employees leave the plant using the emergency exit, and they go to the safe point. The safety manager notes that there are three wounded. The internal emergency team gives them the first care, meanwhile the safety manager calls external healthcare to assess the possible hospitalization. The aim of the model is to evaluate the condition of the injured and to choose the best hospital in which hospitalize them. The case study simulates an emergency management in a dynamic simulation environment using a probabilistic approach to define different variables.

4.1. Phase# 1: Triage hybrid algorithm

Three workers were injured during the incident. Neither of them has absent vital signs, then for all operators is necessary to evaluate triage index. Table 7 shows a triage index chart for operator 1.

Table 7: Triage index (Operator 1)

Triage index (Operator 1)								
Factors	Severity				Weight			Index
	1	2	3	Absent	0.5	1.5	5	
Level of consciousness		x				x		3
Heart beat		x					x	10
Breathing			x				x	15
Mobility	x				x			0.5
Panic	x				x			0.5
Injury		x					x	10
Circulation			x			x		4.5
Ventilation	x					x		1.5
Age	x				x			0.5
								45.5

The assessment injured' condition is performed only by authorized medical personnel. The same analysis is repeated for all the operators with the following results:

- Triage index (operator 1) = 45.5
- Triage index (operator 2) = 47
- Triage index (operator 3) = 35

Table 8 shows the triage assessment for three operators.

Table 8: Triage assessment

Triage assessment			
Operator	Level	Triage index	t (min)
1	Immediate	45.5	10
2	Immediate	47	10
3	Delayed	35	45

4.2. Phase# 2: Rating hospitals

The case study identifies four hospitals near the accident site. The considered criteria are:

- Hospital departments;
- Distance from accident site;
- Number of roads between hospital and accident site;
- Beds vacancies;
- Number of ambulances.

A group of four experts on health and logistic defines criteria preferences using Saaty semantic scale. Figure 4 shows an example of pairwise comparison matrix in a "Superdecision" software. The judgments of experts are significant because CI = 0.03 $\leq$ 0.1. Superdecisions software returns a ranking between different criteria which are used as weights for the next score analysis. beds = 13% , departments = 35%, distance = 32%, road = 13% and transport = 7%. It is necessary to know the conditions of individual hospitals (Table 9) to identify evaluation index (E) for each criterion and hospital.

Table 9: Hospital conditions

Hospital conditions				
Criteria	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Number of departments	6	5	5	5
Distance (km)	3.4	5.5	6	4.5
Roads	3	4	5	5
Beds	370	165	221	234
Transport	2	1	2	3

The evaluation index is a number between 0 and 100 and it is evaluated by considering the information on individual hospitals.

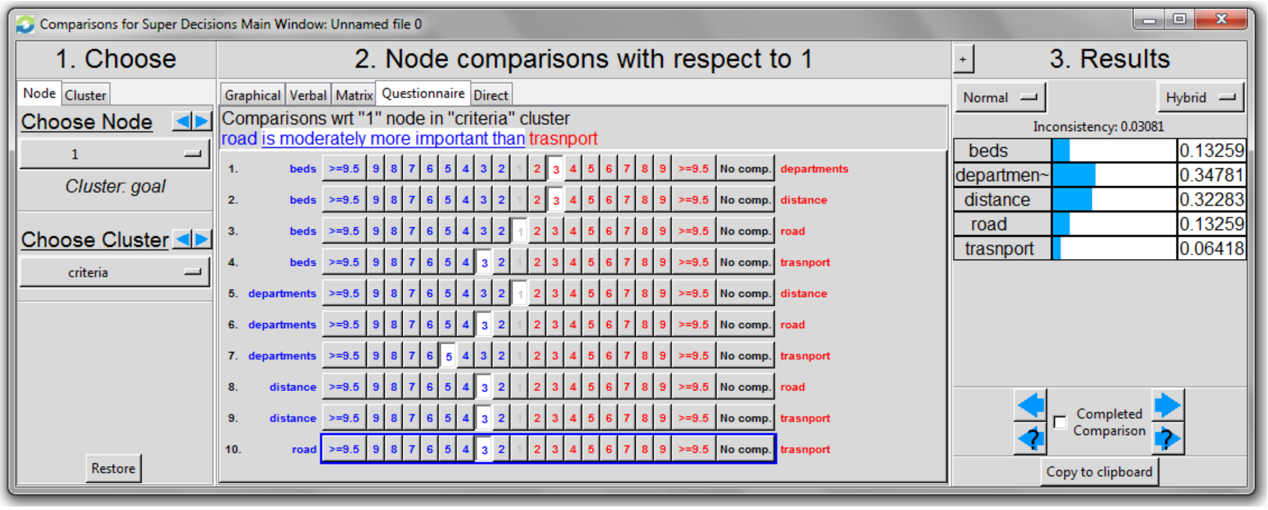

Figure 4: Pairwise comparison – superdecisions software

The evaluation values of table 10 have been developed considering descriptive factors listed in Table 9. For example, considering the number of departments, hospital 1 is the most equipped. So the presented methodology assigns to hospital 1 a value of 90. Other hospitals have all 5 departments, so the methodology associates an evaluation value of 72, slightly lower than hospital 1. Table 10 shows weight and evaluation for each criterion and each hospital. Finally, Table 11 shows efficiency index (WxE) and total efficiency index for each hospital. It shows a hospital ranking. Hospital 1 has achieved the highest score and it is the preferred, followed from hospital 4.

Table 10: Weights (W) and Evaluation (E)

Weights and evaluation					
Criteria	Weight (W)	Evaluation (E)			
		H1	H2	H3	H4
Departments	35	90	72	72	72
Distance (km)	32	90	80	75	85
Roads	13	45	68	90	90
Beds	13	90	40	54	57
Transport	7	90	30	60	90

Table 11: Efficiency index

Efficiency index				
Criteria	W x E			
	H 1	H2	H3	H4
Departments	3150	2520	2520	2520
Distance (km)	2880	2560	2400	2720
Secondary road	585	884	1170	1170
Beds	1170	520	702	741
Transport	630	210	420	630
	8415	6694	7212	7781

4.3. Phase# 3: Simulation

The case study hypothesized an accident in a petrochemical company, that involved different operators. 3 workers are injured and they have been classified using a hybrid triage algorithm (Table 8). A hospital ranking has been defined in Table 11. All wounded should be transported to the hospital 1, because it has the best score. But according data on Table 9, hospital 1 has only two ambulances. So the two "red" wounded are admitted to hospital 1, while "yellow" injured is admitted to hospital 4, which is the second preferred hospital (Table 12). The case study was simulated with "Flexsim 2017" (Figure 5).

Table 12: Strategic emergency plan

Strategic emergency plan		
Operator	Level	Recovery
1	Immediate	Hospital 1
2	Immediate	Hospital 1
3	Delayed	Hospital 4

The simulation shows that 2 ambulances depart from hospital 1 and they will transport "red"operators and 1 ambulance departs from hospital 4 and it will transport "yellow" operator. For model construction it was necessary to reconfigure industrial objects in healthcare objects. For example, the internal industrial handling system is converted into ambulances. Simulation allows to manage the triage process, identifying each patient with a shirt of a different colour related to his triage level. Also simulation manages the logistic process by analyzing the total time necessary for emergency management. Simulation assumptions are:

- ambulance speed: triangular distribution (50, 70, 80,0) km/h. Probability distribution allows to evaluate the different traffic conditions and therefore the different speeds of the ambulance;

- patient load time: triangular distribution (3,5,7,0) min. Probability distribution allows to evaluate the different assessment conditions.

Italian Red Cross defines costs of emergency management. For each ambulance fixed costs are 30 € / journey while variable costs are 0.91 € / minute.

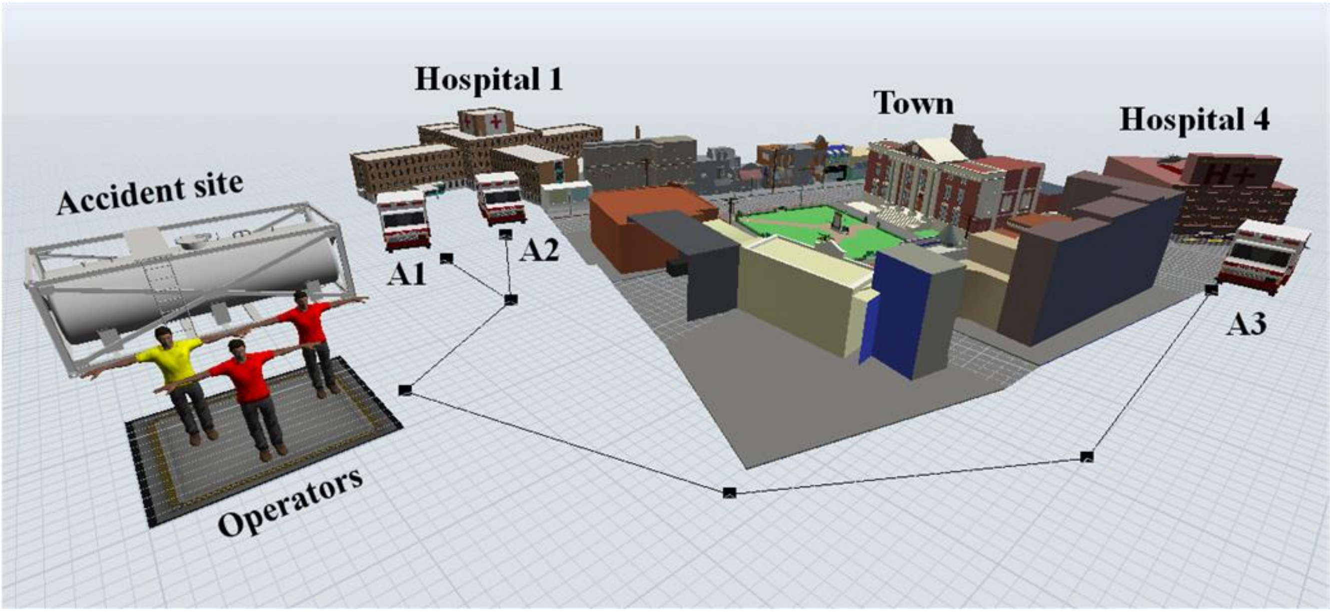

Figure 5: Simulation

These parameters are included in the simulation. Figure 6 shows a typical dashboard of KPIs obtained by Flexsim simulation.

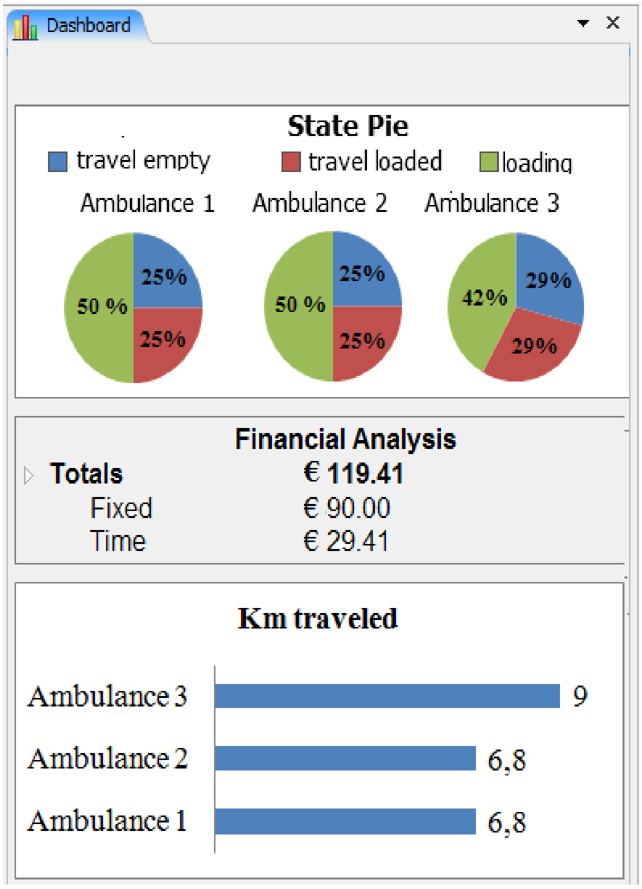

Figure 6: Simulation dashboard

In the first simulation all injured were hospitalized within 13 minutes. The dashboard shows the number of kilometers travelled by 3 ambulances and the percentages of time divided by empty travel, load travel and patients loading time. The highest percentage of time is relative to the patient load. Finally, the simulation also assessed the economic aspect of emergency management. In the first analysis the total cost of healthcare emergency management was 119.41 €. The analysis does not consider the hospital costs.
Ambulance speeds and patient evaluation/loading times are variable, because they are represented by probability distributions. For this reason, 25 simulations were performed to identify the output values variability related to: total emergency management costs (Figure 7) and emergency completion time (Figure 8). The average total cost of emergency management is 120.37 minutes, while the standard deviation is 1.69 minutes. The average time of emergency management is 13.70 minutes, while the standard deviation is 0.74 minutes.

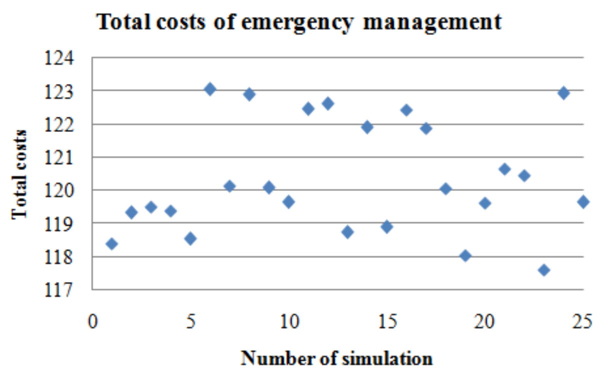

Figure 7:Distribution of costs resultant of 25 simulation

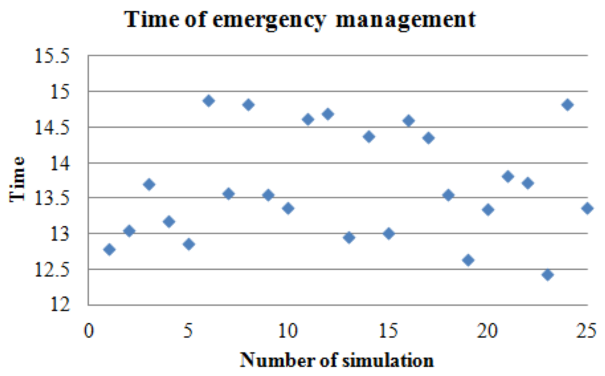

Figure 8: Distribution of time resultant of 25 simulation

5. CONCLUSION

Safety is the most important element in the business management. In particular, during the emergency condition, people are subject to high risks. It is necessary to manage healthcare process, to avoid tragic and deadly consequences. Unfortunately, during emergency situations, the decision maker is subject to a lot of stress, so it could make bad choices. It is necessary to develop a decision support system that helps decision-maker in the healthcare process during an emergency condition. Traditional healthcare models are subjective and do not work with mathematical algorithms. Traditional health management models, that use mathematical approaches, analyze only patient flows, while there are not many TRIAGE mathematical models for patient evaluation in the literature.
The research has developed an analytical-mathematical model which has two objectives:

- develop a hybrid triage algorithm for patient evaluation;
- define a multicriteria mathematical tool to identify a ranking between the nearest hospitals to the accident site.

The two models return numeric values and help the decision maker to make the right decision. The model has been implemented in a real scenario: an accident in petrochemical company in which three workers had been injured. Finally the accident was simulated in a virtual environment with the help of Flexsim 2017 software to identify key performance indicators to manage the healthcare emergency process. The simulation model introduces stochastic variables, so 25 simulations were performed to analyze the variability of two outputs: the emergency management time and the total cost of emergency management.The dashboard obtained with simulation is critical because it allows to evaluate improvements in the healthcare management process through simulation tools. The emergency simulation allows to identify the criticality of the process and make the necessary optimizations.
An interesting future research development is the analysis of the performance variability of emergency processes through new representation models such as the "*functional resonance analysis method*" (FRAM). The goal is to evaluate how a wrong upstream choice can negatively/positively affect other downstream choices.

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AUTHORS BIOGRAPHY

Fabio De Felice, Professor at the University of Cassino and Southern Lazio, board member of several international organizations. The scientific activity developed trough studies and researches on problems concerning industrial plant engineering. Such activity ranges over all fields from improvement of quality in productive processes to the simulation of industrial plants, from support multi-criteria techniques to decisions (Analytic Hierarchy Process, Analytic Network Process), to RAMS Analysis and Human Reliability Analysis.

Antonella Petrillo, Degree in Mechanical Engineering, Phd at the University of Cassino and Southern Lazio. Now Researcher at the University of Naples “Parthenope” (Department of Engineering) where she conducts research activities on Multi-criteria decision analysis (MCDA), Industrial Plant, Logistic and Safety.

Marco Frascio, Degree in Medicine and Surgery. He is Associate Professor in General Surgery, University of Genoa (Italy). Member of the International Society of University Colorectal Surgery from 2013. Since 2008 he is part of the Organizing Committee of the School of Specialization in General Surgery at the University of Genoa. Since 2010 he is part of the Scientific Committee of the Centre for Medical Education, University of Genoa. He is author and co-author of over 300 scientific publications. He is author of seven books.

Francesca Mandolfino, Degree in Medicine and Surgery at University of Genoa (Italy). PhD at University of Genoa. She is author and co-author of several national and international publications.

Federico Zomparelli, degree in Management Engineering at University of Cassino and Southern Lazio. Now, he is a PhD student in Mechanical Engineering at the University of Cassino and Southern Lazio. His research activity is focused on MCDA, lean management, risk analysis and industrial plant optimization.

Marco Esposito, degree in Economics at University of Napoli “Federico II”, he is chartered accountant and auditor. After being General Manager, now he is the CFO of ABC Napoli AS (Public Utilities). He also collaborates with the Faculty of Engineering of University of Napoli “Parthenope” like honorary fellow of Industrial Services Management.