A Study of Crowd Behavior in Emergency Tunnel Procedures

Enrico Briano and Roberto Revetria

Abstract: - In the last years unfortunately some tragedies have occurred inside tunnels (i.e. Mont Blanc Road Tunnel in 1999 and others) causing many deaths and serious injuries for several people, so a greater sensibility towards safety, both in terms of infrastructure and devices but also in terms of people awareness, has been grown.

The authors propose to study the importance of the human behavior and all the factors involving one's choices during the evacuation phase inside a long motorway tunnel.

In order to take into account all the criteria that affect the choices, especially human factors typical of a PECS model, which involves Physical, Emotional, Cognitive and Social behaviors, a multicriteria analysis has been conducted, using Modeling and Simulation (M&S) reproducing a decision network thanks to Saaty's AHP (Analytic Hierarchic Process).

This model is quite similar to the classical PECS models proposed such as Adam Model, in which Adam, thanks to his attributes and knowledge, tries to survive inside his world exploring it and avoiding all the potential dangerous situations; in fact, the person inside the tunnel, thanks to his/her physical, emotional, cognitive and social attitudes (these ones not present in Adam's world where he is alone), has to manage how to survive from a fire or a smoke intoxication reaching safety as soon as he can even sacrificing, at least, an expensive good as a car is.

Keywords: - Emergency Procedures, Human Behavior, PECS, Simulation,

I. Introduction

Safety in tunnels has become important in the last years because a significant price has been paid in terms of human lives inside these structures; in fact, especially after the tragedy inside the Mont Blanc Tunnel in 1999, in which 39 people died and hundreds were intoxicated or seriously injured, the European Union introduced very restrictive regulations about safety devices in road and railway tunnels, especially for those longer than 1000 meters, introducing for instance the emergency tunnel, which is parallel to the normal one and guarantees a safe escape way on foot, smoke detectors, ad hoc traffic lights which break the vehicle flow, especially heavy, in case of accident or high pollution level.

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Anyway the people that are involved in an emergency situation, because every people behave and react in different way, provide a great importance also, in order to guarantee the highest percentage of safety, because a wrong choice, maybe guided by the hurry or by fear and anxiety, could be paid at a high price.

The aim of this research is in fact to study the people behavior during an evacuation of an about 4,5 km long motorway tunnel, considering all the parameters and the phenomenon which affects the people's behavior

II. State of the Art on Crowd Behavior Simulation

Crowd behavior simulation has been an active field of research, since the 90s, because of its utility in several applications like emergency plannings or evacuations, it is also useful to study the design and planning of pedestrian areas, the people flow in subway or rail road stations and also in education, training and entertainment.

Lee and Son used Believe Desire Intention (BDI) architecture to model a crowd simulation useful for human decision making and planning and using different techniques, like the Bayesian Belief Network (BBN), Decision Field Theory (DFT), and Probabilistic Depth First Search (PDFS), for related sub-models [15].

BDI is a model of human's reasoning process, where its mental state is characterized by three components: beliefs, desires, and intentions [3]. Beliefs are information which human has about the circumstance, and may be incomplete or incorrect due to the nature of human's perception. Desires are the states of affairs which human would wish to be brought about. Intentions are desires which human has committed to achieve.

In this case they applied the methodology for modeling an evacuation of Washington D.C. because of a terrorist bomb attack: starting from the scenario they characterized different types of agents based on:

familiarity with the area,
risk taking behavior,
confidence index,
guidance by police

Depending on these agents' features, the evacuation behaviors will be different.

As seen before, the sub-models have been implemented using techniques like BBN, DFT and PDFS; The first one has been used in order to give some environmental information like smoke, fire, police, crowd, and distance including

evaluation of values for attributes (risk and evacuation time) for the considered option (a path from an intersection)

weights on each attribute.

The weights on each attribute at time t, are obtained from 'RiskWeight' node in the BBN network.

DFT and PDFS have been used to realize the real-time planner sub-module in the decision- making module of the proposed extended BDI.

Kaup (and al.) introduced, in the crowd simulation, some parameters that could affect the people behavior, in a special manner the age factor: they studied the behavior of three different types of crowd, one made by young children (3-8 years), one made of middle aged people (18-40 years) and one made by older people (70+ years), considering the following characteristics varying with the age of the group:

Personal Space (How close is an individual willing to be in relation to obstacles or other individuals),

Speed (How fast does an individual prefer to move),

Randomness on the individual's motion

Considering now the middle aged group the mainline for which the original simulation parameters were constructed, children are expected to see them making more erratic movements, and tending to move faster than the other groups. In addition, children would generally be willing to get much closer to both obstacles and other individuals, while the older individuals would tend to move more slowly and be much more conscious of the spacing between themselves and others [16].

The results provided by this study are pretty surprizing: the children, thanks to a speed doubled respect to the base case, have a lower density than the baseline simulation, while, on the contrary, older people, because of a speed which is a half of the base case, stretches to a denser crowd near other people and obstacle points, despite their best consciousness of distances and space constraints. The results can be graphically compared in the figures from 1 to 3

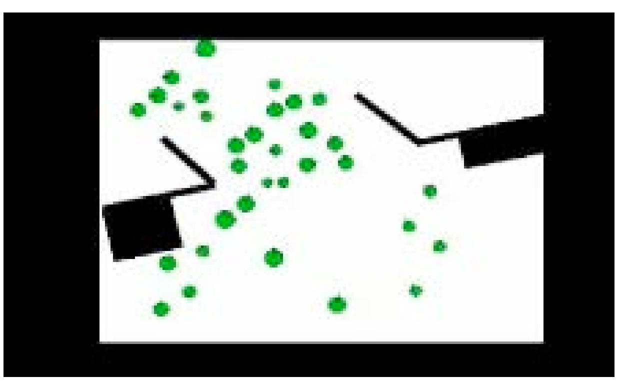


Fig. 1 – Baseline crowd Movement in Kaup et al.

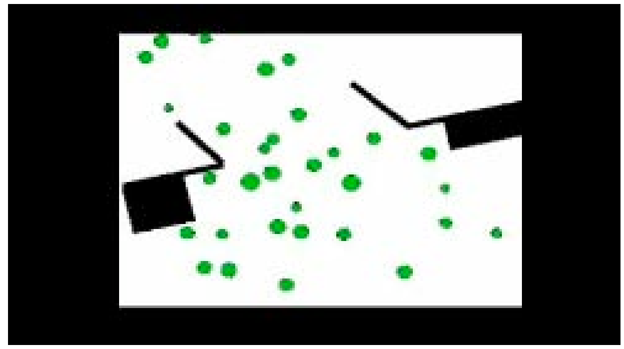


Fig. 2 – Children crowd Movement in Kaup et al.

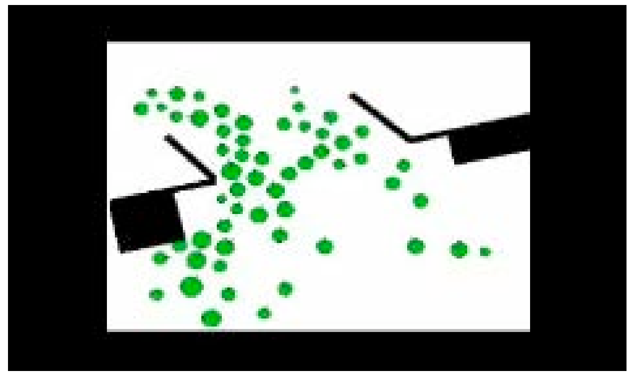


Fig. 3 – Older People crowd Movement in Kaup et al.

Banerjee, Abukmail and Kraemer modeled an agent-based crowd simulator using a simple agent model, leading to a scalable simulation system [13].

In this case the intelligence is distributed in the terrain instead of accumulation into a complex model that each agent has to follow.

In particular they focused on crowd movement on a 2D terrain using layered AI framework in order to create an efficient platform for agent movement which could be expandable in order to incorporate behaviors more and more complex.

The 2D surface field of the action is divided into square grids where can hold at maximum one person, and all the informations are distributed into layers that, combined, provide simple navigation decisions [14].

For instance, the Occupancy Layer provides the agent's current position, while the Obstacle layer indicates if a cell presents a solid obstacle (walls, etc...).

Consulting these layers the agent should be able to avoid collisions and eventual enemies correctly planning its path to the final destination.

According with the classical human behavior modeling theory, and using a similar structure of terrain, a PECS model has been taken into account, because it is the model that best fits for this situation, in fact, during the evacuation procedures, the behavior is affected by physical (i.e. tiredness), emotional (i.e. fear, anxiety), cognitive (i.e. knowledge) and social (i.e. interaction with other people) aspects.

As seen on introduction, the classical literature proposes the

PECS model as the best suitable to study human behavior, so an explanation of what a PECS model is need to be provided.

III. The PECS Model

PECS is a multi – purpose reference model used in simulation of human behavior in a social environment [4]; human behavior is quite complex on its structure because it is influenced by physical, emotional, cognitive and social factors, so the human being is consequently perceived as a psychosomatic unit with cognitive capacities who is embedded in a social environment. (Notice that PECS is the acronym of Physical conditions, Emotional state, Cognitive capabilities and Social status).

The PECS model is an evolution of the BDI (Belief Desire Intention) architecture [3,15], which was no more appropriated for sophisticated models aiming to model real social systems.

In all forms of behavior control the physical situation, the emotional state, cognitive abilities and social position play a role. If human behavior is to be modeled and hence made comprehensible and predictable, the following state variables have to be taken into account:

Physical State Variables
Emotional State Variables
Cognitive State Variables
Social State Variables

In some models the combination of all the 4 variable classes is not required, any possible combination depends on the nature of the problem and the model. The decisive factor is that it must be possible to construct complex models which contain all the four classes mentioned and do not disregard their interactions.

In the case presented by the authors, the model involves all the 4 classes, using architecture quite similar to Adam Model [6], but with the substantial difference due by the presence of the social aspect: the human being that has to evacuate the tunnel is not alone, but he/she has to interface with other people.

A. A Simple Example of PECS Model: The Adam Model

The aim of the Adam Model is to show a simple human behavior model according with PECS' references [1]. In order to keep the model simple, the social component has not been considered; in fact Adam lives alone inside his environment.

Adam lives in a world which is a square of 12x12 fields, with a representation quite similar to the layer structure provided from Banerjee et al. in the introduction; inside there are:

Neutral Fields in which nothing happens
Food Sources where Adam can eat and replenish his energy level
Danger Points from where Adam needs to escape consuming a significative amount of energy.

A representation of Adam's world is shown in figure 4.

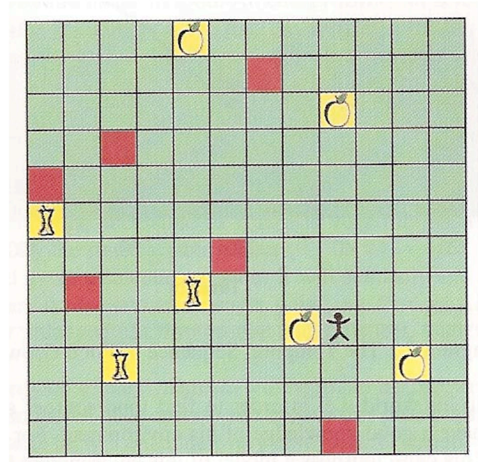


Fig. 4 – Adam's World

The Adam model takes these facts into account:

Adam's Environment: The world where Adam lives in is dynamic, it constantly change: the world contains food sources and danger points and Adam has to face with these continuous changes of environment.

Physical, Emotional and Cognitive State Variables: Adam's internal state is first characterized by the state variable of energy, which is a physical one. In addition he has also the emotional variable of fear and cognitive state variables about the model of his environment he has. There are no social variables because Adam lives alone inside his world.

Changes of the internal variables: Internal state variables are not constant, they change continuously both autonomously either if triggered by an input. As an example given the energy state variable will slow automatically decline; but if Adam falls in a danger point, the effort to escape is so great that the energy decrease is slighter; on the contrary, when Adam finds a food source, the energy level increases depending on the amount of food consumed: the more is the food eaten, the more the energy will increase towards the max. The emotional state of fear behaves similarly: when Adam becomes more confident with his world, the fears level decreases, reaching the zero value, but when Adam discovers a danger point, fear has a slight increase.

Reactive and Deliberative behavior: Adam's behavior contains reactive and deliberative elements, in fact he follows simple rules when, for example, he is guided by the hunger motive or when he has to think, but he is also capable of deliberative behavior, planning a series of actions that allow him to reach the goal that he knows to be achieved. Adam has also a kind of self-image, which influences his actions and their parameters.

Internal and external actions: Adam's behavioral repertoire contains both external and internal actions; external actions, which affect the environment where Adam lives in, are, for instance, action focused on moving towards food and gathering it, while internal actions affect only Adam himself, such as when circumstances trigger the action of thinking.

Learning: Adam knows some processes typical of the environment he lives in: he knows, for instance, that food, once eaten, needs time to grow again and replenish the field, but initially he does not know the replenishment speed and so he has to learn it. When Adam's knowledge becomes more developed, it is easier for him understand the food replenishment speed and so taking the appropriated actions.

Forgetting: Adam is a human being, and so he is subjected to forgetfulness, so, after a certain time, he does not remember if inside a certain field there is a neutral point, a food source or a trap, so he has to "refresh" his memory revisiting the fields.

Some of these aspects, according to the circumstances, can be proposed inside the tunnel evacuation model.

IV. The Evacuation Model

As seen before, the model proposed by the authors, has some points in common with Schmidt's Adam Model, but the Social aspects, that were not necessary inside Adam's model due to Adam's loneliness in his world, play a significant role, in fact the tunnel, which is located in a mountain motorway and it is about 4,5 km long, is full of people in queue with their cars, buses and trucks, causing a traffic jam: inside the tunnel something negative occurred: a fire or a smoke intoxication.

One of the people inside has to deal with the problem and he has to decide what to do to save his life: escape leaving the car inside or stay in because the problem could be solved probably in a few minutes.

The aim of the research is to define what aspects affect a person's choice in that situation, which is potentially dangerous, and to find a solution devoted to define the correct choices taking into account all the parameters and the factors that affect the choice itself in an analytic way.

This study is surely comparable to a Multi Criteria Decision Analysis (MCDA), and so one of the most suitable applicable methodologies is no doubt the AHP (Analytic Hierarchic Process) developed by American Mathematician Thomas L. Saaty [7-8].

Let's briefly explain the mathematical theory which leads the AHP and ANP methodologies:

Consider n elements to be compared, C1 ... Cn and denote the relative 'weight' (or priority or significance) of Ci with respect to Cj by aij and form a square matrix A=(aij) of order n with the constraints that aij = 1/aji, for i <> j, and aii = 1, all i. Such a matrix is said to be a reciprocal matrix.

The weights are consistent if they are transitive, that is aik = aijajk for all i, j, and k. Such a matrix might exist if the aij are calculated from exactly measured data (Figure 5).

$$\mathbf{A} = \begin{vmatrix} a_{11} & a_{12} \dots & a_{1n} \\ a_{21} & a_{22} \dots & a_{2n} \\ \dots & & \\ a_{n1} & a_{n2} \dots & a_{nn} \end{vmatrix}$$

Fig. 5 – Saaty's Weight Matrix

Then find a vector ω of order n such that Aω=λω. For such a matrix, ω is said to be an eigenvector (of order n) and λ is an eigenvalue. For a consistent matrix, λ=n.

For matrices involving human judgement, the condition aik = aijajk does not hold as human judgements are inconsistent to a greater or lesser degree. In such a case the ω vector satisfies the equation Aω= λmaxω and λmax ≥ n. The difference, if any, between λmax and n is an indication of the inconsistency of the judgements. If λmax = n then the judgements have turned out to be consistent.

The representation of the matrix product Aω is shown on figure 6.

$$\begin{vmatrix} w1/w1 & w1/w2 & \dots\dots\dots\dots & w1/wn \\ w2/w1 & w2/w2 & \dots\dots\dots\dots & w2/wn \\ \dots\dots & & & \\ \dots\dots & & & \\ wn/w1 & wn/w2 & \dots\dots\dots\dots & wn/wn \end{vmatrix} \times \begin{vmatrix} w1 \\ w2 \\ w3 \\ \dots \\ wn \end{vmatrix} = n \begin{vmatrix} w1 \\ w2 \\ w3 \\ \dots \\ wn \end{vmatrix}$$

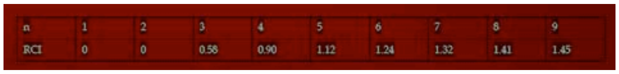
Fig. 6 – Matrix Product Aω representation

Finally, a Consistency Index can be calculated from (λmax-n)/(n-1). That needs to be assessed against judgments made completely at random and Saaty has calculated large samples of random matrices of

increasing order and the Consistency Indices of those matrices. A true Consistency Ratio is calculated by dividing the Consistency Index for the set of judgments by the Index for the corresponding random matrix. Saaty suggests that if that ratio exceeds 0.1 the set of judgments may be too inconsistent to be reliable. In practice, CRs of more

than 0.1 sometimes have to be accepted. A CR of 0 means that the judgements are perfectly consistent.

The final step is to calculate the Consistency Ratio for this set of judgements using the CI for the corresponding value from large samples of matrices of purely random judgments using the table below (figure 7), derived from Saaty's book, in which the upper row is the order of the random matrix, and the lower is the corresponding index of consistency for random judgements.



n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Fig. 7 – RCI (Random Consistency Index) related to the matrix order

The authors considered the model as a multi criteria network, in which different aspects (physical, emotional, cognitive and social) are considered as state variables and affect the decision with their own weight.

The objective function of the study is to avoid the fire or the intoxication, and to do it there are two different alternatives: escape outside leaving all inside or wait in the car trying to save all, not only their own life.

The result of the objective function is driven by the so-called "High Level Criteria", which in the authors' case are the following:

Save the Car

Save the Life

Panic

Other People's Behavior

All the four criteria takes into account the four aspect of the PECS Reference Model, in fact the first two criteria involves both physical and cognitive aspects, while panic is strictly connected with the emotional sphere and others' behavior belongs to the social state variables.

The authors' model is quite similar to Adam Model because the individual has to survive inside his world (the tunnel) trying to preserve his energy avoiding danger points and using his knowledge in order to try to save life, car and all the personal effects inside it.

The emotional aspect of panic, which increases when something negative happens (an exit closing, a fire exploding, etc…) but slowly decreases when the situation is going to normalize (an emergency squad arrives, more information are available, etc…), also affects the behavior of the man in the tunnel.

The four High Level Criteria are at their time divided into sub-criteria which are coincident with the state variables of the problem: two concerning the car saving, two for the survival preserving, three for the panic [12] and two for others' behavior.

In detail they are:

Economy (related to the car): leaving the car inside could cause the loss of an expensive good that is not trivial to re-buy

Car's Youth: it is more difficult for a person to leave a new car than an older one

Health: preserve health level is the most important aspect and so the variable with the highest weight and importance

Family: safety is important also for the family which, even if not directly involved in the situation, is seriously worried about the man's life, especially when they know the news by other means (police, mass media, etc…)

Exit Closing: the number of the exits closed affects the panic level, the higher is the number of closings, the higher is the panic level

Negative events occurring: when a new negative event, such as a fire or an explosion, occurs, the panic level slightly increases

Lack of Info: people have a panic increasing when they have no information and they do not know what to do

Other People Escaping or Staying: Others' behavior could affect the man's choice because "he does what the others do".

A network representation is shown below in figure 8.

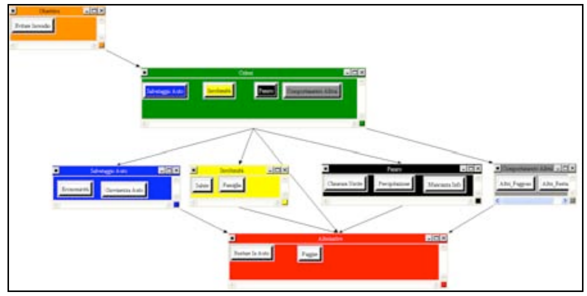


Fig. 8 – AHP Network Representation

All these factors have been related to their own high level criteria and to the two different alternatives with a different weight according to the preference, the probability or the importance: Saaty typically assigns a judgment from 1 to 9 in terms of importance, that affects the weight's value, according with the criteria shown in the table below [9]:

Judgment	**Importance**
1	Equal
2	Between Equal and Moderate
3	Moderate
4	Between Moderate and Strong
5	Strong
6	Between Strong and Very Strong
7	Very Strong
8	Between Very Strong and Extreme
9	Extreme

The research provides, in a further step, to analyse the situation in which the person involved in the evacuation has already decided to escape from the tunnel and then he has to do another choice: towards which sign where to go considering a set of different alternatives, valid and misleading. Also in that case a model in Super Decisions(TM) has been implemened considering a new objective function, which is the sign choice, and new criteria and subcriteria. In this case the High Level Criteria are five:

Visibility: the signs have to be bright, near and visible even also in case of smoke; In fact a person could be oriented to follow the nearest sign of fire extinguisher or emergency exit or the most visible one

Experience: a person could have experiences in terms of rescue, considering fire preventing and medical experiences, and knowledge of emergency signs

Utility: the sign could be useful to preserve the person's own life, or to rescue others' lives, but there are also signs which are misleading and provide no utility.

Fear: also in this second step panic could seriously affect the people's choice as well as in the first model

Others' Behavior: as seen for fear, it is proposed in the same way as in the first part of the analysis, considering interaction with others.

The alternative considered are a set of possible signs to follow; The person in fact could decide to head himself to a fire extinguisher, to a medical kit, to the emergency exit or to other signs that could be not useful to save lives.

This second part of the case study present some subcriteria and so a more complex network to analyse, as shown on figure 9.

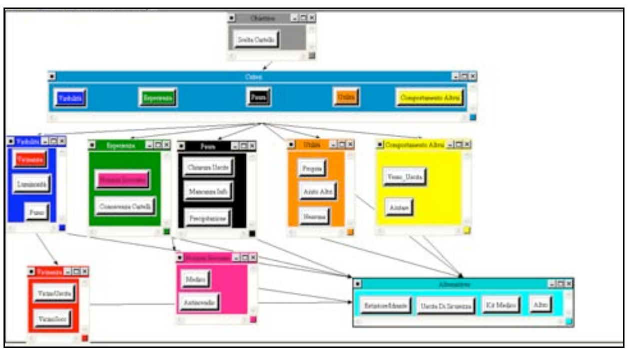


Fig. 9 – AHP Network Part II Representation

V. Results of the Research

As seen before, for every criteria, sub-criteria and alternative, a weight has been assigned, according to the judgment table seen in the last paragraph. Now let's going to show some significant results of the research, starting from the impact of the high level criteria on the objective function:

The most important parameter for the objective function is no doubt the health safety aspect (66,66%), followed by the car saving (16,67%) and, at least, both the panic and others' behavior (8,33% each), as shown on figure 10.

Notice that the Inconsistency index is equal to 0, while an acceptable value is any under 0,1 [10].

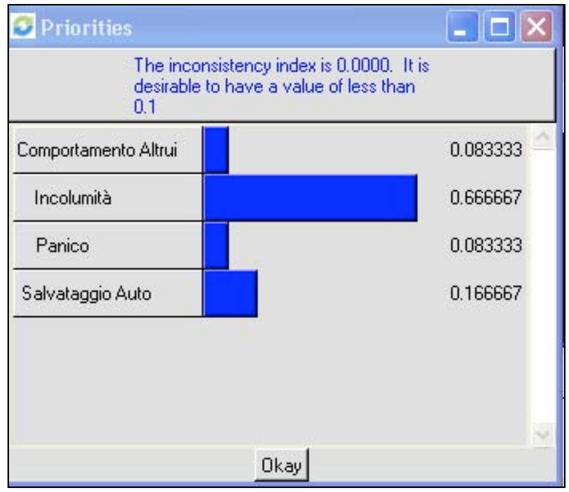


Figure 10 – Results of High Level Criteria Impact on Objective Function

As a further example, let's see the impact of the panic state variables on panic level increasing:

The factor with the highest impact is the negative event occurring (66,66%), followed by the exit closing (26,67%) and the lack of info (6,67%).

Also in this case the inconsistency level is 0, as the figure 11 shows.

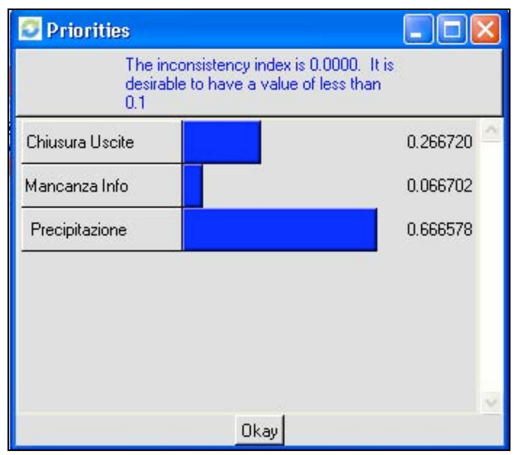


Fig. 11 – Impact of Panic State variables on Panic Level

Finally let's have a look to the final results: taking into account all the weights, factors and parameters, it is possible to discover if the best alternative is to escape from tunnel or stay in the car.

As shown in figure 12, the best choice is to escape (72,7%) instead of staying in the car (27,3%)

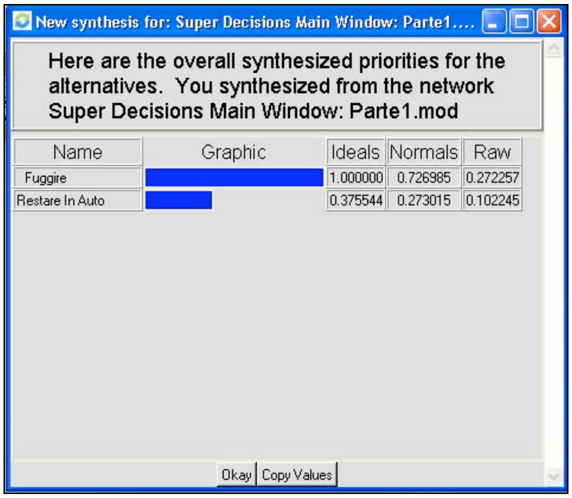


Fig. 12 – Part I Global Results

The second part of the authors' research proposes to investigate, as seen on the previous chapter, another human behavior model derived from this first results: in case of escape, the man has to decide what to do, if running towards a fire extinguisher or an emergency exit, considering the interaction with other people and the knowledge about first aid, fire fighting procedures and emergency signs, knowing what sign to consider and what signs to discard.

In this phase some interesting results has been extrapolated: first of all let's consider the importance of the five high level criteria on the objective function (the right sign choice): a rational person consider more important first of all the sign visibility, even also in bad condition like in a smoke saturated tunnel (38,5%), then, later, the sign utility (22,6%) and the personal experience (21,9%); Obviously fear and others' behavior have to be less considered making the hypothesis of rational behavior. The inconsistence value in this case is 0,0182, ten times smaller than the maximum acceptable value, which is always 0,1.

The results are shown in figure 13.

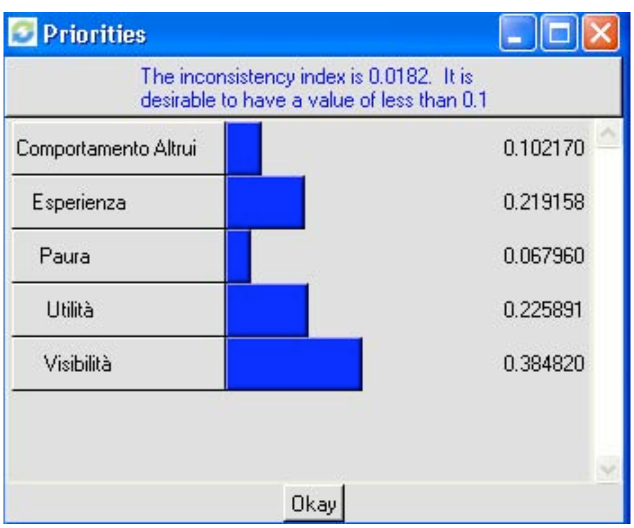


Fig. 13 – Impact of High Level Criteria
On Part II Objective Function

Now let's analyze the impact of the subcriteria of brightness, distance and smoke presence on visibility: the most significant factor is no doubt the distance of the sign, in fact the person aims to follow the nearest sign in order to stress less himself (69,2%), then the brightness on the darkness of the tunnel (23,1%) and, last, the smoke presence (7,7%). In this case there is no inconsistence and the results are shown in figure 14.

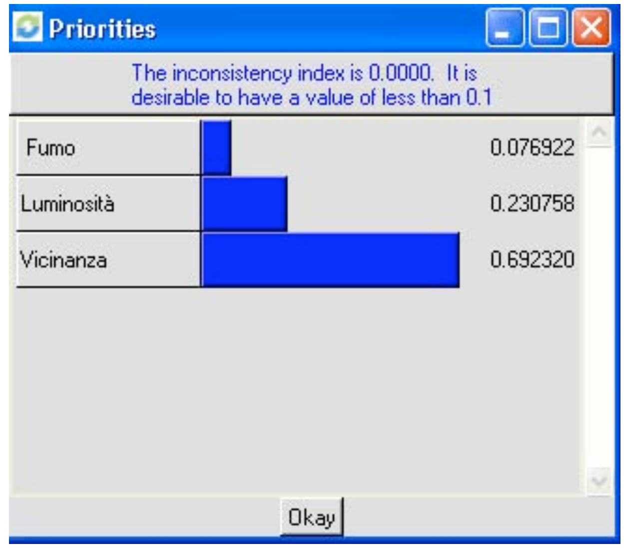


Fig. 14 – Impact of Smoke, Brightness and Distance on Visibility

Considering now the impact of the visibility on the alternatives, it is clear that the most visible sign is the emergency exit, because of its green color that immediately meets the person's eyes (47,6%), followed by the medical kit and the fire extinguisher with the same percentage (23,8% each), and then the other signs (4,8%). Also in this node comparison the inconsistence is null, as the figure 15 histogram shows.

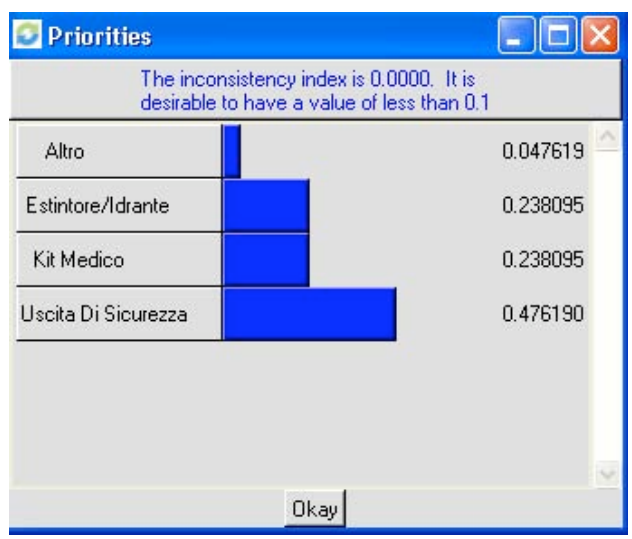


Fig. 15 – Impact of Visibility on Alternatives

Finally the global results has to be analyzed: considering all the criteria and subcriteria the best sign choice need to be determined, so the whole model has been synthesized: the winning alternative, among the four presented, is to follow the emergency exit sign (44,4%), because probably life preserving is the most important thing, then the fire extinguisher (25,3%), which requires a bit of experience on fire fighting, then the medical kit (22,3%), because first aid need to be operated only by expert subjects, and then other signs (8%) not very useful.

The results are also shown in figure 16.

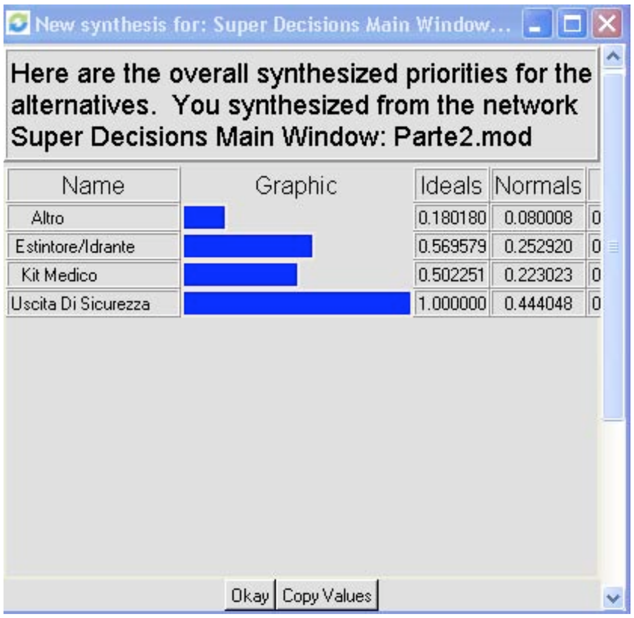


Fig. 16- Part II Global Results

In this kind of situation, where an homogeneous loss of flammable substances or other dangerous materials may be occur, it is possible to study a simulation of the behavior of these substances using a model proposed by (Giribone et al.) [17].

The model can be ideally divided into two blocks, one that describe the first phase, the evaporation phase, in which there are as input:

total released [kg],

initial temperature of the gasoline [K],

initial ground temperature [K],
pool surface A[m2],
wind velocity w[m/s],

conductivity of the ground [ ]

diffusivity of the ground [ ],

thermal conductivity of air [ ],

viscosity of air [ ]

Prandlt number of air .

The output of this block about the transient phase and the finish conditions are:

Real time pool height variation ΔH [m/s]

Real time pool temperature variation Δt[K/s],

Gas volume flow rate qs[Kg/s].

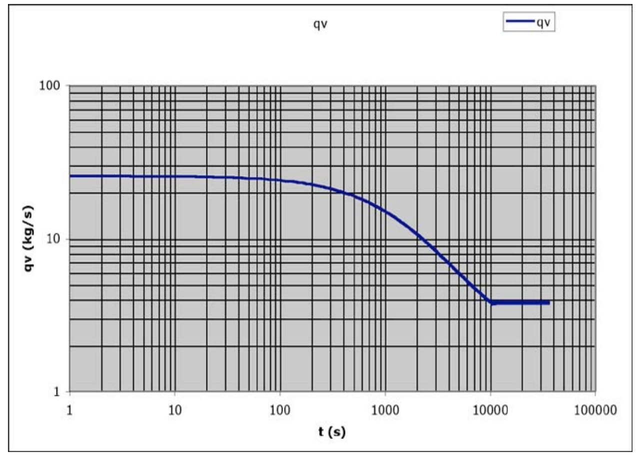


Fig.17 - An example of gas evaporation flow rate

The most important one is the evaporation rate that is variable but, as shown of the figure 17, reach a constant value due to the equilibrium between the latent and evaporation heat. The heat necessary is taken from the solar, ground and atmospheric heat flux, as shown in Fig.18. It possible to observe a constant decreasing of the temperature of gasoline till a constant equilibrium value. This outputs can be used to evaluate the time necessary to create a critical mass of vapour. Data were found for 32 different scenarios given by the combination of input.

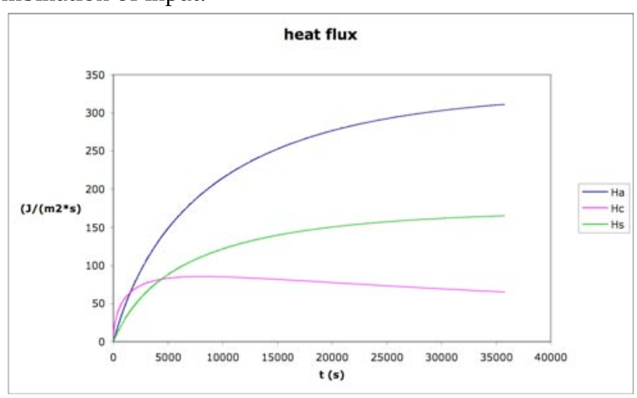


Fig.18 - The heat fluxes Ha, Hc, Hs

The second block of the model is more complex than the first one, it use a system of six differential equation to find the first set of output and it use this results to solve the equation that gives the gas spatial concentration in the cloud.

$$\begin{cases} \frac{d}{dx}\left(2\rho u b_y b_z\right) = 2\rho_a\left(b_y 1.5\sqrt{3}k(u_*)_{ic}\frac{1-\frac{b_z}{h_i}}{f_h\left(\frac{b_z}{L}\right)} + b_z\sqrt{3(0.209k\Delta u)^2 + 3\left(0.08\frac{\left(f_s(L)f_p(t_{av})\right)^2}{\left(f_s(L)f_p(t_{av}) + 0.0014b_y\right)}\right)^2}\right) \\ u\frac{db_y}{dx} = \frac{\rho_a}{\rho}\sqrt{3(0.209k\Delta u)^2 + 3\left(0.08\frac{\left(f_s(L)f_p(t_{av})\right)^2}{\left(f_s(L)f_p(t_{av}) + 0.0014b_y\right)}\right)^2} + u_y \\ \frac{d}{dx}\left(2\rho u u_y b_y b_z\right) = 2g\cdot(\rho_0 - \rho_a)b_z^2 - 0.5\rho b_y u_y^2\left[\left(\frac{u_*}{\langle u_a\rangle}\right)^2 + 0.0195\left(\frac{\rho_a}{\rho}\right)^2\right] \\ \frac{d}{dx}\left(2m\rho u b_y b_z\right) = 0 \end{cases}$$

$$\begin{cases} \frac{d}{dx}\left(\rho u b_y b_z c_p T\right) = 2\rho_a\left(b_y w_{e,t} + b_z w_{e,e}\right)c_{p,a}T_a + 2\rho b_y\frac{u_*}{\langle u_a\rangle}(u_*)_{mg}c_p\left(T_a - T\right) \\ \frac{d}{dx}\left(2\rho u^2 b_y b_z\right) = -\rho_a\frac{d}{dx}\left(2g b_y b_z^2\right) + 2\rho_a u_a\left(b_y w_{e,t} + b_z w_{e,e}\right) + -2\rho b_y\left(\left(\frac{u_*}{\langle u_a\rangle}\right)^2\left[(u - \Delta u) - \langle u_a\rangle^2\right] + 0.0195\Delta u^2\right) \end{cases}$$

$$c(x,y,z) = 2b_y b_z\frac{\mu_a m(x)}{\left(\mu_s + (\mu_a - \mu_s)m(x)\right)}\frac{1}{4y_b}\left[\mathrm{erf}\left(\frac{y + y_b}{\sqrt{2}C_y}\right) - \mathrm{erf}\left(\frac{y - y_b}{\sqrt{2}C_y}\right)\right]\frac{1}{\sqrt{(2\pi\sigma_z^2)}}\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right]$$

Fig.19 The mathematics equations of the second block

This second block use as input:
Gas volume flow rate qs[Kg/s].

Air density

Initial cloud density
Air temperature Ta[K]
Initial cloud temperature To[K]
Pool surface As[m2]
Initial pool speed u0 [m/s]
Wind speed at 10 m height ua (10)[m/s]
Pasquill stability class
Terrain type coefficient
Effective gravity [m/s2]
Von Karman constant
And some others.
The outputs of the dispersion model are:

Spatial concentration c

cloud density

cloud temperature

m mass concentration of the chemical fluid spilled

u cloud downwind speed

cloud crosswind speed crosswind

cloud width/2

cloud height

Fig.20 - The level of concentration related to the distance from pool

The second series of mathematic equations were used to found the possible dimensions reached by the cloud making the hypothesis of a constant release of the vapour after the transition phase. The model was used to draw several graphics of the final dimensions of the cloud after the wind effect.

The model can make an analysis to find which near objects, operators or tanks undergo the effects of explosion. Dimension and velocity of the explosion can take to different effects. In this contest the flame front speed the most important parameter, 10m/s of flame front speed take to a limited effect, but a faster speed as 40-50m/s, can take to a pressure ad heat wave, that can make serious injuries to the plant and fatal effects for the people. The model can trace the final dimension of the region were the explosion of the cloud and the following disaster. It was possible to define the critical region were the concentration of the gas reach the LEL Low Explosion Limit and the 172 LEL. This is the concentration in percent of volume of gas in air necessary for the immediate explosion caused by an external cause. In the matlab 3D representation is possible to evidence by colours the height grow of cloud, as shown in figure 21.

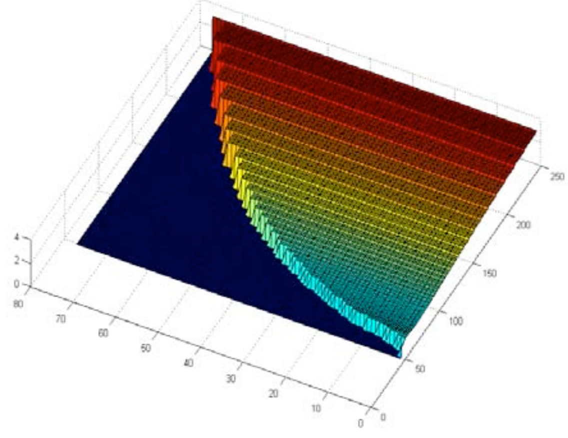


Fig.21 The semi-cloud elaborated by matlab distances in m

In conclusion it is clear that with this work the human behavior in a very critical situation such as a tunnel evacuation has been studied, and, behaving in a rational way, without considering fear and others' reaction, it is certain to make the best choice to save human lives.

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