

Assessing large scale emergency rescue plans: an agent based approach

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Abstract- In this paper we describe a multi-agent based approach for modeling and simulating the dynamics of large scale crisis situations. Our aim is to show how agent-based approach can benefit modeling-simulating a complex socio-technical collaborative complex system. The development of the model and simulator is based on data obtained from field studies of quasi-realistic non-computer based simulations and from official French rescue plans. Using our agent-based simulator we conduct samples of tests of various combinations of heuristics, both real and hypothetical in order to assess various potential rescue plans. To illustrate this, we focus on two organizational strategies combined with two communication modes to assess how they affect rescue process efficiency in terms of the global evacuation time and the rescue rate. Seven selected configurations have been simulated for each of the four typical scenarios ((centralized or distributed strategy) and (traditional paper or new electronic forms)). These first simulations show that: (1) electronic communication reduces delays and victims losses; (2) although distribution strategy improves rescue in general, centralized rescue process remains the most efficient in case of having many victims and few rescuers.

Index Terms—Large scale rescue, centralized and decentralized control, rescuer behavior, communication artifacts.

1. INTRODUCTION

In order to be adequately prepared for emergency situations it is necessary to be able to assess in some way the effectiveness of the intended plans and strategies. One way of accurately assessing the outcome of emergency plans is to perform quasi-realistic simulations. However, for large scale accidents, performing such live field simulations is becoming increasingly difficult and expensive. Such simulations are also of limited value since they allow only a few scenarios to be re-enacted. Nonetheless, live-simulations are fundamental for understanding the characteristics of the situation, the interactions and the cooperative activities of the actors involved in this shared environment, and in understanding how crises are managed. Nevertheless, the fact remains that such experiments are largely impractical for assessing the dynamics of crisis situations.

One tool which has proven to be extremely useful in investigating complex organizational systems is agent-based simulation. Crisis and emergency management is a perfect example of a *collaborative and distributed complex system* where various agents (victims, doctors, fire-fighters, police-officers) each with *heterogeneous*,

complementary and *interwoven* competences and having various roles, organize themselves dynamically in groups and teams, adapting their behaviors, continuously processing incoming information, and reacting in an unpredictable way to their environment. It is now widely accepted that if a problem domain is particularly complex, large, or unpredictable, and the system is distributed and open, then one of the most efficient ways of exploring the problem is to use multi-agent systems (MAS) [10, 16]. To date, numerous agent-based simulations have been developed in many domains (e.g. [4, 11, 15, 17]). In particular, several studies have shown that this approach can be used for the design of complex organizational systems in a crisis situation [1, 7, 13, 14].

The aim of our work is to develop an agent-based simulator able to model the dynamics of large scale crisis situations, encompassing the collaborative and social nature of the rescue activity, in order to compare different rescue strategies. Our approach is based on applying various heuristic algorithms to each agent and component of the simulator. The simulator allows us to conduct tests of various combinations of heuristics, both real ones which represent actual existing rescue strategies, as well as new and hypothetical ones which enable us to test alternatives and to help in designing new solutions.

The main objectives of this computational modelling approach are to understand, answer, and solve different questions and problems concerning emergency rescue in large-scale accidents. The first and immediate questions aim at understanding rescuers collaboration on site and design optimal, efficient and adequate rescuing plans: how does the initial state of victims affects the performance of rescuing? How does the number of each type of rescuers affect the rescue activities? How does the communication mode affect rescue performance? More broadly, we are interested in how an agent-based simulator can help design new collaboration technology solutions.

The following section attempts to characterize large scale rescue situations and to outline the main steps in providing emergency medical care. The design, the development and the validation of the agent-based simulator are provided. Following a description of a sample of experiments showing how the resulting virtual environment may support concretely decision making by assessing various potential rescue plans. To illustrate this, we focus on two organizational strategies combined with two communication modes to assess how they affect rescue process efficiency in terms of the global evacuation time, the percentages of losses of lives and the rescue rate. Seven selected configurations (with varying numbers - reaching

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300 agents- and types of victims and rescuers) have been simulated for each of the four typical scenarios ((centralized or distributed strategy) and (paper or electronic forms)). The paper concludes with a discussion on the results.

2. LARGE SCALE ACCIDENT RESCUE

An accident is an unfortunate, harmful event, caused unintentionally where one or many persons become victims and need rescuing interventions [1]. When hundreds and thousands of people are involved and when damages are high such an accident can be considered as large scale one. Therefore, according to the type and seriousness of the accident, different emergency plans – usually referred to as Rescue Organization plans - are provided. They contain a theoretical prepared and predicted description of the hierarchical organization of the rescue teams and the responsibilities of each of their members as well as the main steps. The plans aim to rescuing victims, performing better evacuation results (reducing live and material losses: extinguishing fires, unblocking routes, etc.), reducing delays and minimizing the number of dead victims. Although these plans have been meticulously prepared they are not always followed exactly. Indeed, the teams use flexible heuristics coordinating themselves to adapt to new emerging events. The decision processes involved in the evolution of a crisis situation are complex and only partially understood. Several mechanisms, which often work simultaneously, have been identified to explain the dynamics of such groups: (1) the multi-casting and overhearing mechanism imply the non-deterministic propagation of information among actors ([7, 13]); (2) the role of artifacts (objects in the environment) in explicit and implicit communication [18]; (3) the role of verbal and non verbal interactions [9]; (4) the emergent process in the collaborative activity and self-organization phenomena [12]. In addition, the environment plays a large role in the rescue process since it influences the scope of communication, the search strategies of the rescuers and victims, and the spread of physical phenomena (e.g. fire).

Crisis management is different from many other socio-technical systems. It proceeds simultaneously according to two organization modes and therefore its dynamic is controlled by both: (1) well organized and structured processes (team hierarchy, prescribed roles, defined rules of intervention, etc. all of which are well codified in advance as rescue procedures); (2) emergent processes which cannot be controlled by the actors since, in reality the defined procedures can never be performed as predicted and the teams have to adapt continuously their resources, action modes, composition, structure, etc.

In order to understand the rescue process we have worked closely with SAMU¹ teams who conduct quasi-

realistic, non-computer based simulations of crisis situations for training purposes. This collaboration consists mainly on fieldwork, where observations were made, interviews were conducted, and rescue plans exercises were videotaped, analyzed and discussed with rescue actors (firemen and medical staff). For example, two of our team researchers have actively participated to the Orly Red Plan Simulation, which took place in Paris, near the Orly Airport on February 2004. It consists in simulating a plane crash, involving 73 victims (role played by young firemen), and where doctors, firemen, nurses coming from the airport rescue staff and from the surrounding prefectures have been involved. In total, 207 persons played this four-hour-simulation. The data obtained from field studies of such simulations has been used to construct our simulator. Our study is also based on two official French plans: the White Plan [8] which concerns the intervention of the medical resources at the site of the accident, and the Red Plan [14] which concerns fire-fighters interventions.

The emergency medical care consists of the following main steps [8]: 1. Assessing the medical needs of victims. 2. Identifying victims, moving the victims if necessary and providing essential medical care. 3. Categorizing the victims according to the seriousness of their injuries and the situation, orientating the victims. 4. Evacuating and transporting the victims. 5. Retrospectively elaborating the victims' medical summary reports.

This rescue organization process can be formalized as a digraph. In Fig. 1, the nodes (represented by rectangles) correspond to key activities to be performed and the arcs represent the potential alternative transitions from one node to another. Two nodes can be connected by multiple links if there are many transition strategies. The continuous lines show the main rescue path and the dotted ones show alternative options. As the process is collaborative where each node can be performed by one or many actors simultaneously, we extend the graph by annotating each node (represented as dotted rectangle) with its set of possible couples (*executor, enactment context*); where *executor* refers to the potential roles/actors who could execute this activity and *enactment context* defines the associated set of conditions under which each actor would act. Effective enactment of steps may follow one or many heuristics. Therefore, a set of heuristics may be associated to a node or a transition.

Given this representation, aiming to summarize the complexity of the rescue process, the problem of defining an efficient rescue plan becomes that of finding efficient paths in such digraph.

3. DESIGN OF THE AGENT-BASED SIMULATOR

We have designed a computer simulator, which is a virtual environment, taking into account the actors, their activities and interdependencies as well as the environment in which they are collaborating. It mimics the observed team collaborating. Furthermore, not only it supports experimentation with new scenarios, and it is also a generic

¹ SAMU: Service d'Aide Médicale en Urgence (one of the principal French medical and emergency rescue services).

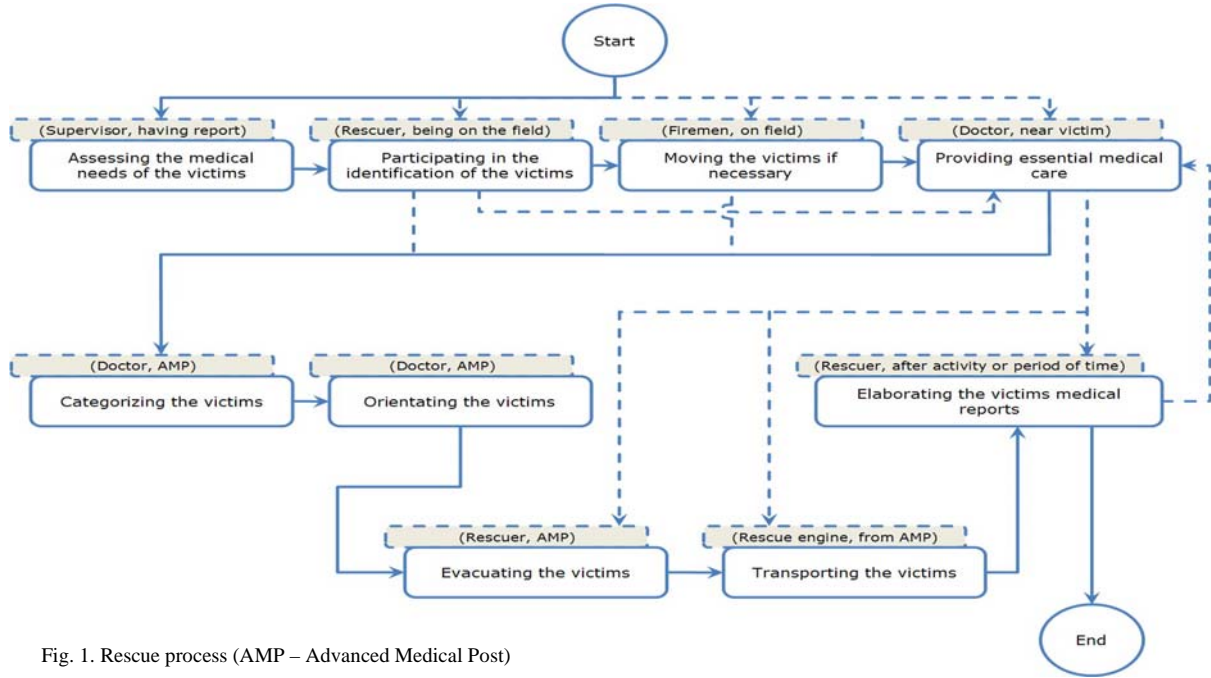


Fig. 1. Rescue process (AMP – Advanced Medical Post)

tool offering reusable modules. We have followed an Agent-Oriented approach to design and develop our model and simulator in an iterative way.

3.1 The Model

According to the vowels model ([5, 6]) the main components of a multi-agent system are: **A**gent, **E**nvironment, **I**nteraction, **O**rganization, and **U**sers. A brief description of each of these components together with an interpretation for our model is as follows:

3.1.1. Environment

The Environment refers to the domain dependent elements for structuring external interactions between entities. In our model it represents the whole city, including routes and hospitals, or the different areas where accidents occur. The environment encompasses the areas where victims are initially situated, where doctors explore and treat victims and where rescuers perform evacuations. Each area is referred to as incident field or *site*. For rescuing activities, each site is considered as one whole *zone* or may be split into many distinct sub-zones. In all cases, the environment as a geographic map of the accident site, is defined by its size, in terms of width and height, expressed in cells. Therefore, a cell refers to an elementary unit to represent graphically the environment. The site dimensions are used as the reference for describing the relative site arrangement and the actors' location within the site at each step. Furthermore, aiming to build a model which is generic per accident and location (symbolizing many different kinds of accidents such as floods, fires, etc. in urban areas or not), we introduce two independent abstractions to characterize each cell on the site: an *obstacle* describing a cell through which no one could pass (e.g. buildings) and a *danger* referring to a point through

which only fire-fighters can pass (e.g. fires). A cell which is neither an obstacle nor a danger is considered *normal*. An Advanced Medical Post (AMP) is interactively positioned, at the beginning of the simulation, on the field so that it is not far from the focal point of the accident and so that it is close to the routes to facilitate evacuation. Hospitals are positioned as well. Victims and rescuers can be spread randomly or placed interactively on the map.

3.1.2. Agents

The autonomous Agents define the internal architecture of the processing entities. Victims and rescuers are the main agents of our model:

Victims: Victims are modeled as reactive agents with a continuously evolving degree of health gravity which is a function of the environmental properties of the victim's location (normal or dangerous cell) and the rescuers intervention and treatment.

According to medical sources [8], a five step scale of gravity is used: 4 = Not Serious (called U3); 3 = Serious (called U2); 2 = Very Serious (called U1); 1 = Extremely serious (called EU); by extension, 0 = Dead. States 4 and 3 are referred to as a "Relative Emergency" whereas states 2 and 1 are referred to as an "Absolute Emergency".

For the dynamics of evolution of each victim, we adopted a Markov Chain, per type of cell, and per type of intervention, defining the probabilities of transition from one state to another over time. Fig. 2 shows an example of the defined probabilities for an evolution in a normal cell without any intervention from rescuers.

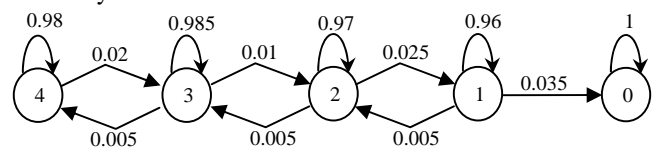


Fig. 2. Markov chain of the transition of gravity in a normal cell

Such a probabilistic view enables us to express intuitive facts and to implement flexible heuristics related to modeling victims. Heuristically, we state that:

- HV-1: “In a normal/safe cell, and without intervention from rescuers, a victim has a greater chance to remain in the same state, a very low chance of getting better autonomously and a low chance of getting worse”
 - HV-2: “In a safe cell, a doctor’s stabilization of a victim’s status makes the probability of remaining in the same state greater (by reference to values of HV-1) and reduces that of getting worse”
 - HV-3: “In a safe cell, a doctor’s treatment of the victim in his or her initial location increases the probability of getting better (by reference to values of HV-2) and reduces that of getting worse”
 - HV-4: “In AMP and/or in ambulances and hospitals, the probability of improving the victim’s status increases and that of getting worse decreases, by reference to the values of being on site”
 - HV-5: “In dangerous cells, and without rescuers action, the probabilities of getting better are less than for HV-1, and to get worse are greater than for HV-1”
- As for HV-2, HV-3 and HV-4, three rules are stated by adjusting probability values by reference to HV-5 taking into account doctor’s stabilization, or treatment or victim’s transfer to AMP or hospital.

Rescuers: Rescuers (supervisors, doctors, nurses, fire-fighters) have perceptive and cognitive intelligence which enables them to understand their environment according to a structured representation. More precisely, a rescuer in his field of perception can distinguish a victim from a nurse or a fire-fighter, a danger cell from an obstacle or a normal cell. There are also manager agents which can act as supervisors at various levels (the General Rescue Director, the Local Area Chief, the AMP chief and the Material Park Coordinator) who are able to capture information about the situation from all rescuers spread over the incident site directly or via communication devices. Except victims, which are modeled as *inanimate agents*, all other agents are *animated* and can move around the site alone or to transport victims. In order to model the rescuers behaviors, heuristic algorithms have been implemented for each step of the rescue process:

- **Site exploration** is undertaken by the rescuers who are assigned to a zone by the General Rescue Director. The rescuers search for victims and identify the global properties of the incident in order to assess its level of gravity. Rescuers exploring this area can follow HRE-1 (*conforms to reality*) or HRE-2 (*a hypothetic new case*) where:
 - HRE-1: explorers move *randomly* in the area, but only fire-fighters can pass through a dangerous cell.
 - HRE-2: to minimize the exploration time (recognized in field studies as a source of inefficiency), explorers should cover the entire area in an *organized* way, without visiting the same cell more than once and

avoiding obstacles and dangerous zones (except fire-fighters who can pass through the latter).

- **On site treatment** is carried out by doctors finding victims (heuristics HRF-1, HRF-2, HRF-3), examining them and assessing their status (HRA-1, HRA-2, HRA-3). The rescuer can thus decide on the necessary treatment according to the victim’s evolution gravity history and the availability of resources (HRT) and can then assign an evacuation priority.
 - HRF-1: while walking on the site, a doctor looks for the nearest or the first victim within her/his field of visibility whether (s)he is just entering the site or not (*perception guided finding*).
 - HRF-2: if the doctor has already visited the site, (s)he goes towards the nearest already known victim (*memory guided finding*).
 - HRF-3: if the doctor has already visited the site, (s)he goes towards the most seriously injured and already known victim (*memory guided finding*).
 - HRA-1: examination is based on questioning the victim if possible and/or direct capture of medical measures and observation (blood pressure, breathing rate, etc.).
 - HRA-2: examination is based on reading the victim’s evolution history from the *medical paper form* associated with each victim when available (*conforms to reality*).
 - HRA-3: examination is based on reading the victim’s evolution history from an *electronic medical form* associated with each victim when available (*this is a new design situation intended for real situations*).
 - HRT: this global heuristic relates to the rescuer’s treatment behavior and follows the recommendations of consulted medical experts who stated that: (1) victims with a status of ‘Absolute Emergency’ need stabilizing first and/or on-site treatment and receive a higher priority for evacuation than other victims; (2) victims with a status of ‘Relative Emergency’ do not usually need to be stabilized and receive a lower evacuation priority.
- This behavior is repeated by each visiting doctor until there are no more victims untreated in this zone. Intermediate reports are continuously made by doctors to the General Rescue Director in order to provide a global overview of the rescue so that resources may be better assigned for transfer and evacuation.
- **Victim’s transfer to AMP** is carried out by one or two nurse(s) and/or fire-fighters, under the supervision of the General Rescue Director, until all of the victims have been transferred. The transfer adheres to the following intuitive rule: “A higher transfer priority is given to alive victims and according to their Relative or Absolute Emergency status”.
 - **Victim’s evacuation to hospital:** on arriving in the AMP, and after initial treatment, victims should be transferred to the appropriate hospitals by ambulance teams as soon as possible according to their health gravity

and evolution; this occurs under the supervision of the AMP Director. Heuristics have been developed to encompass these points.

- **Ambulance's routing towards known hospitals** has been implemented according to the Dijkstra Algorithm by searching the shortest path linking the AMP (departure point) to the hospital (arrival point) through the network of routes existing on the city map. This assumes that the ambulance driver knows perfectly the whole city and that all routes are available. In future work, we would consider dynamic routing, taking into account unknown areas, traffic jams and blocked routes, etc.

- **Management of the centralized rescue** by the General Rescue Director is performed according to the amount of available resources (i.e. manpower - doctors, nurses and fire-fighters), knowledge of the incident level and the known number and state of victims, in order to provide "the most help with least resources".

- **Management of the distributed rescue:** This is a new rescue design strategy intended for real situations. It consists in managing rescue without a General Rescue Director; where rescuers act as autonomous sub-groups, having each its own chief. Such teams may collaborate with each other by exchanging rescuers according to situation needs and rescuers availability.

3.1.3. Interactions

The Interactions are the elements for structuring the internal interactions between the entities included in our model: (a) Interactions between actors and the environment (mainly perception, exploration); (b) Interactions among rescuers who are exploring the site, evacuating by pairs, and communicating directly or via artifacts. In fact, as observed and reported from real situations, traditionally, each victim is identified by means of an evacuation medical form, which is attached to him/her, including the civil state (identification) of the victim or the descriptive sate (for not identified ones), the medical check –up and the gravity scale (EU, U1, U2, U3). On disaster site, doctors report victim's state and score on such pre-numbered paper forms and then transmit that same information to the SAMU center. A new way is intended to be designed based on electronic medical card and instantaneous uploading via wireless Local Area Network connections. Therefore, each doctor would report victim's data on an electronic card. In this case, there would be no extra time or activity for sending information to the centre since the transmission would be done instantaneously and automatically after each card update. (c) Interactions between the user and the simulator environment, by monitoring the rescue process and running simulation step by step.

3.1.4. Organization

The Organization defines the elements for structuring sets of entities within the MAS. In the simulator, we

consider both the centralized strategy used in real life and distributed strategies. This is chosen interactively at the configuration phase of each simulation.

3.1.5. Users

The User interface permits the initial configuration of the simulations (e.g. number of victims and their states, the adopted strategies, the rescuer's behaviors, number of ambulances, etc.) by stating new values or by loading them from a database; drawing or loading existing city maps; identifying key points (AMP, hospitals); continuous visual control of the rescue process (e.g. site overview, graphics, text descriptions, intermediate reports, supervisor knowledge); dynamic parameter changes during the simulation (e.g. adding new victims, rescuers, dangerous zones or obstacles), and step-by-step simulation.

3.2 Simulator parameters

As soon as the main model bricks are built, assumptions are made and adequate parameters are chosen. Therefore, a set of parameters and potential associated values are defined to express the model components' properties to deal with their characterization and dynamics as well. In deed, we have mainly:

- Environment parameters: size, number of included dangerous and obstacle cells, included routes, rescue resources in terms of hospitals (number, location, capacity of each), AMP (location, state, etc.), ambulances (number, location, speed, etc.),
- Agents' parameters:
 - Victims: total number, percentage per gravity degree, Markov chains transition probabilities per type of cell and received treatments,
 - Rescuers: numbers per role, and for each rescuer and according to its category some of the following parameters are given: role, location on the site, speed, visibility, state (moving, treating, transporting, ...),
- Interactions' parameters mainly among rescuers and with victims: different delays are assigned to each elementary action to describe communications (e.g. delays to read/write using a paper medical form are greater than those of using electronic devices, transmission delays for electronic devices are considered null) and treatments (e.g. diagnosis, improvement),
- Organizations' parameters are set to define distributed or centralized strategy with division into zones or not,
- Users' parameters such us the rate to update the graphical displays.

Consequently, a great set of parameters are introduced with this model. They are of two kinds and serve two complementary purposes:

- All parameters modeling existing/observed concrete components involved in rescue situation must be calibrated to deal with a realistic rescue process and get up with a trustable simulation environment for decision makers. By calibration, we mean tuning and adjustment of values so

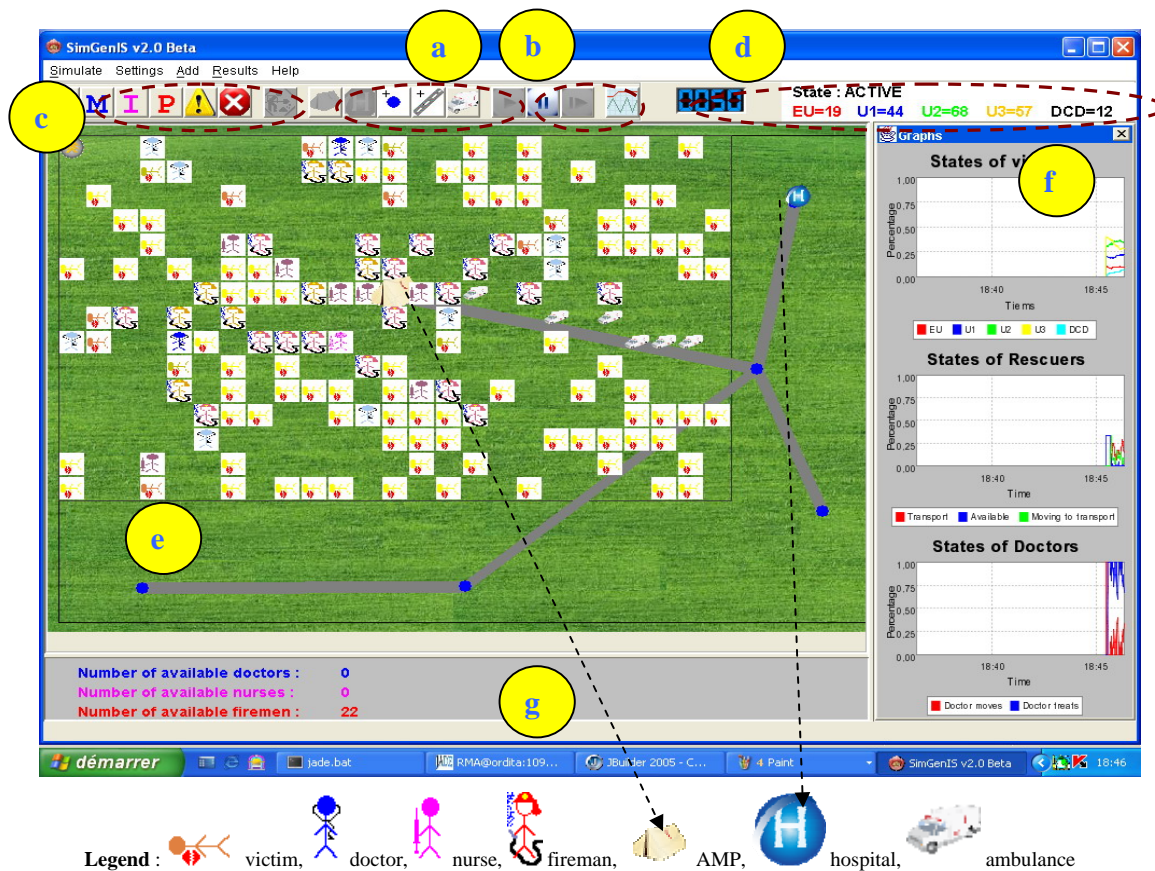


Fig.3. Overview of the simulator interface

that they represent realistic states evolutions and behaviors. Victim's gravity transition probabilities, relative behavior's delays are significant example of this.

- All parameters enabling to test different rescue scenarios for different kinds of accidents in different environment (e.g. numbers of victims and rescuers) make the second subset of parameters which represents the sets of input values for one what-if simulation scenario.

4. GENERIC AND INTERACTIVE AGENT-BASED EMERGENCY RESCUE SIMULATOR: SIMGENIS

SimGenis, is developed using the multiagent platform JADE (Java Agent DEvelopment Framework) (version 2.5) (available at <http://jade.tilab.com>) and is written in the java language (running under Sun JDK 1.4 Java Virtual Machine). Jfreechart 0.9.4 (available at <http://www.object-refinery.com/jfreechart/index.html>) library is also used. SimGenis is also connected to a database (Microsoft Access for instance). It is written as modules organized in three packages: *ontology* package with 40 classes, *simulator* package with 37 classes, and *graphs* package with 5 classes.

The simulator interface provides Input, Output and Control widgets and displays. In fact, as shown on Fig. 3., SIMGENIS includes mainly:

- Configuration panels enabling the user to set, for one simulation scenario, adequate parameters via the settings (sub-)menu(s) and/or interactive buttons (Fig. 3.-a),
- A control panel enables the user to run a simulation step by step or continuously, and to stop it (Fig. 3.-b),
- Actors (victims -V-, doctors -M-, nurses -N-, firemen -P-) can be interactively placed on the site; an obstacle or a danger can be associated to a cell by a drag and drop button too (Fig. 3.-c),
- A clock (expressed in steps) and numbers of victims per category are updated at each step (Fig. 3.-d),
- A main display providing an overview of the accident site shows the spatial positioning of AMP, hospitals, routes, victims and the location and status of cooperating rescuers. Different colours, which change according of the agent's state, enable the user to follow in real-time the evolution of the rescue process. For example, default colour associated to a victim is yellow, changes to light green when this agent is under treatment by one doctor and becomes light brown when visited at least once. (Fig. 3.-e),
- Graphic windows show the number of victims per gravity degree, and also the state of each kind of rescuers over time (Fig. 3.-f),
- A textual trace of execution reports on the simulation events and its evolution. (Fig. 3.-g).

Additional interface windows, not shown on Fig. 3., are provided to catch relevant rescue process features: control windows show the status of each agent at each step and the communication acts exchanged during the whole simulation. The AMP related events are also mapped and shown graphically.

Output results, events, and the agents' status are written to an event database and to files which can be further analyzed using statistical tools, such as SPSS.

5. ABOUT THE VALIDATION

Validation is a crucial issue mainly when the developed model and simulator aim to support effective decision making. General discussions of validity for computational models point to one or more of the following six types of validation: conceptual, internal, external, cross-model, data and security [3]. Conceptual or theoretical validity refers to the adequacy of the underlying conceptual or theoretical model in characterizing the real world. Internal validity refers to whether the computer code is correct and the program is free of coding errors. External or operational validity is concerned with the adequacy and accuracy of the computational model in matching real world data.

In our case, we have applied conceptual, internal and external validation levels guided by each of the vowels bricks of our model [2]. For the conceptual level, we worked jointly with the experts to define the model components. For the internal and external validation of our simulator, in order to check that the programs are free of coding errors, combinations of parameter values have been given as input to the simulator. Exhaustive extreme values of parameters have been voluntarily tested to study the simulator behaviours. Real scenarios, corresponding to field work results have been used. For example, to calibrate the transitions probabilities of victim's gravity in a normal cell and without any rescue attendance, hundreds of simulations have been conducted. For each probability, a range of values is chosen with experts; then for each value, simulations are run with 100 victims as unique agents; all victims have the same gravity degree corresponding to the node which probabilities are being tuned. Also, since for a given node, probabilities are dependent, we proceed progressively from state 0 to state 4.

6. Virtual experiments and results: towards Relative assessment of rescue strategies

Full tractability has been one of our major considerations while developing SimGenis, building therefore wide temporal simulations databases, with various variables (dependent and independent). Our aim, by doing so, is to provide all potential data for deep analysis and scenarios assessments. In what follows, we draw an example of using our simulator showing how to run new virtual experiments and to discuss "what if" scenarios. In this paper, we present samples of experiments and their simulation results, which answer the following

research questions: (1) what is the impact of the rescue organization strategy on rescue process performance? (2) How do communication forms among rescuers affect rescue efficiency? (3) How does the rescue process evolve according to victims' numbers and initial states and/or to rescuers numbers and missions?

We ultimately aim to explore for a given disaster a good "tradeoff" between victims and rescuers to ensure better rescue minimizing losses and reducing delays.

6.1 Virtual experiments design

The virtual environment covers two families of scenarios: real and hypothetical. Experiments are designed by combining choices of the main strategies and related heuristics: (1) The environment may be limited to just the incident field or extended to cover a whole city including one or many incidents, routes and hospitals; (2) The rescue organization strategy may be centralized or distributed; (3) the incident field may be considered as one area or divided into sub-zones; (4) the rescuers actions may include exploration or may prioritize evacuation; (5) each doctor may organize her/his actions according to the distance to, or the severity of, the victims.

There are 64 main cases and each one identifies a rescue plan which may be instantiated by a set of configuration variables and parameter values.

6.2 Efficiency criteria definition

In order to assess and compare rescue scenarios, efficiency criteria must be defined. Since we stated that the aim of emergency rescue plans is to rescue the most victims with the shortest delay we will initially consider the following efficiency criteria:

- GET = the Global Evacuation Time of all victims = when all victims are off the incident field;
- RR = the Rescue Rate = (number of alive victims at GET) / (number of alive victims on initial time)
- RD = the Rate of Death = (number of dead victims at GET) / (total number of victims)

According to the experiment aim, additional qualitative and quantitative results may be defined, such as the Evacuation Time of First Victim (ETFV), the Relative Loss Rate (RLR) (ratio of number of supplementary dead victims from initial time to GET by number of alive victims at start time), Rate of Absolute Emergency (RAE) (ratio of number of Absolute Emergency Victims at GET by number of Absolute Emergency Victims at start time), Rate of Relative Emergency (RRE) (ratio of number of Relative Emergency Victims at GET by number of Relative Emergency Victims at start time). What is important to underline, that all elementary variables, necessary to compute such criteria, may be extracted from the simulation traces.

6.3 Virtual scenarios tested and related configurations

In order to assess the efficiency of the rescue process according to the practiced decision making strategy and to

the used communication mode, we choose the following four experiments:

- **Experiment 1:** Simulation of a city with one incident field and one AMP, according to **centralized** strategy considered as **one zone**, where doctors treat (without a first exploration) and nurses evacuate victims beginning from the nearest ones; and where medical **paper** forms are used.

- **Experiment 2:** same as experiment 1 but uses **Electronic** devices instead of paper forms.

- **Experiment 3:** Simulation of a city with one incident field, according to **distributed** strategy considered as **four sub-zones**, where doctors treat (without a first exploration) and nurses evacuate victims beginning from the nearest ones; and where medical **paper** forms are used.

- **Experiment 4:** same as experiment 3 but uses **Electronic** devices instead of paper forms.

Experiment 1 represents the scenario similar to the quasi realistic rescue process. It is our reference scenario serving as our benchmark. The three other experiments are examples of new rescue heuristics that may be applied.

In order to assess the relative impacts of rescue properties on each other and on the efficiency of the whole process, we consider various initial configurations and simulate each of the previous four experiments.

The selected configurations vary from each other as follows:

- **Configuration 1:** The initial values are consistent with the quasi-realistic Red Plan simulation used by the emergency services in Orly, Paris, France: Apart default values, we have **73 victims** (5% in state 1; 7% in state 2; 13% in state 3; 20% in state 4 and 55% dead), **75 rescuers** (15 doctors, 60 nurses), and 8 ambulance teams, 1 hospital with a high bed capacity (see Fig. 3. for the hospital and AMP location).

- **Configuration 2:** In this case we modify the above situation by assuming all victims alive at start time. This would inform us, what would be the rescue results if we begun earlier, before getting victims dead. Therefore, we keep the previous configuration where only the initial victims states are changed : **73 victims** where **60%** in state 1; 7% in state 2; 13% in state 3 and 20% in state 4.

- **Configuration 3:** By reference to configuration 1, we consider now twice the number of victims and keep the percentages per state. This would inform us on the impact of getting more victims to be rescued by the same rescue team. Therefore, we keep the configuration 1 where only the total victims number change: **146 victims** where 5% in state 1; 7% in state 2; 13% in state 3; 20% in state 4; and 55% dead.

- **Configuration 4:** In order to assess the impact of increasing the number of rescuers, we modify configuration 1: **150 rescuers** (30 doctors, 120 nurses).

- **Configuration 5:** Contrarily to configuration 4, we decide here to reduce the rescue resources, and keep the victims configuration: **35 rescuers** (5 doctors, 30 nurses).

- **Configuration 6:** In this case, we consider higher numbers of victims and rescuers: **200 victims** (10% in state 1; 20% in state 2; 30% in state 3; 40% in state 4; and 0% dead) and **90 rescuers** (20 doctors, 40 nurses, 30 fire-fighters).

- **Configuration 7:** In this case, we consider high number of victims and reduced number of rescuers: **200 victims** (10% in state 1; 20% in state 2; 30% in state 3; 40% in state 4; and 0% dead) and **35 rescuers** (10 doctors, 10 nurses, 15 fire-fighters).

Table 1: Configurations' characteristics

Configuration	total number of victims	Number of alive victims	Number of rescuers	Number of rescuers/total number of victims
Config. 1	73	33	75	1,03
Config. 2	73	73	75	1,03
Config. 3	146	66	75	0,51
Config. 4	73	33	150	2,05
Config. 5	73	33	35	0,48
Config. 6	200	200	90	0,45
Config. 7	200	200	35	0,18

Table 1 summarizes these configurations, and illustrates their variety in terms of relative numbers of rescuers and victims (alive or not).

Since our model is highly based on probabilities and stochastic variables, we present our results as mean and standard deviation of 10 runs for each simulation, of the global evacuation time (GET expressed in steps) as well as the percentages of victims per state at GET. All data given in the following results from simulations conducted on a same computer (Pentium 4, 3 Giga hertz, 512 M RAM) in the frame of few days. Within, this configuration, a time step is one second time machine. A simulation run completes when all victims are evacuated.

Due to our computer resources (mainly in terms of RAM capacities), we were not able to launch more than 300 agents. We are working on developing distributed (among a grid of PCs) version of the simulator enabling running thousands of agents to cope with real large scale disasters. Furthermore, given that firstly all configurations are done manually, secondly we aim here to show the "how to use the simulator and assess the rescue plans" much more than the "what is exactly the best", thirdly simulation is time consuming, we voluntarily restricted for this paper the simulations runs to 10. We intend to make deeper analysis and research on the required simulation repetitions to get out with usable decisions in real situations.

6.4 Results and interpretation

In this section, we give and discuss the results of simulating the four experiments with each of the seven configurations. Intuitively, a good approach should be to minimize GET (Global Evacuation Time) and maximize RR (rescue rate).

Table 2: Summary of results for the first experiment repeated for seven configurations

Configuration		GET	%EU	%U1	%U2	%U3	%Dead	%RR	GET/RR
Config. 1	Mean	70,9	4,2	8,2	17,8	13,3	56,4	96,80	73,24
	Std. dev.	11,92	1,5	2,3	3,7	3,3	1,4		
Config. 2	Mean	72,60	30,7	17,0	18,5	12,9	21,0	79,04	91,85
	Std. dev.	18,06	3,2	3,4	3,6	2,7	2,9		
Config. 3	Mean	139,10	4,4	8,6	19,0	10,4	57,6	94,22	147,64
	Std. dev.	35,55	1,5	1,8	2,0	1,4	1,1		
Config. 4	Mean	58,50	4,2	7,3	19,3	12,7	56,4	96,80	60,43
	Std. dev.	14,17	1,2	1,6	3,1	2,5	1,3		
Config. 5	Mean	139,4	4,8	9,2	19,5	10,0	56,6	96,5	144,46
	Std. dev.	30,48	3,0	3,0	2,7	2,8	1,7		
Config. 6	Mean	143,4	9,9	22,0	39,1	20,8	8,2	91,8	156,19
	Std. dev.	14,92	2,9	2,2	2,6	1,7	1,9		
Config. 7	Mean	199,4	11,1	21,7	37,8	18,3	11,2	88,8	224,58
	Std. dev.	25,78	1,0	1,9	2,7	2,8	1,9		

1st experiment results: simulation of quasi-realistic scenario: centralized strategy and paper form

In a first stage, we simulate the quasi-realistic rescue process with each of the seven configurations. The obtained results are shown in Table 2. We present the average and standard deviation of GET and percentages of victims per state, and the rescue rate (RR) as well as the ratio of GET by RR.

This table shows that:

- By comparing config. 1 to config. 2 (testing the fact that rescue process begins “earlier”, where 60% of victims are in extreme serious state and still not dead): GET values are close to each other in both cases; config. 2 gives only 21% of losses of lives instead of 56,4 %; relative emergency states (U2 and U3) are close to each other. Although the value of rescue rate (RR) for the first configuration is higher, and the ratio GET/RR is lower than those of configuration 2, the latter is better, because the RR value is calculated on the basis of alive victims at start time (45% for config. 1 compared to 100% for config.2).

- By comparing config. 1 to config. 3: By doubling the number of victims and by keeping the same rescue resources, we notice that GET is almost doubled (139,10 for config. 3 versus 70,9 with config. 1), where as the rescue rates remain close to each other. This highness of rescue efficiency, in terms of RR, may be explained by the fact that although the total victims’ number is high, the number of alive ones is close to rescuers’ number as shown on Table 1.

- By comparing config. 1 to config. 4: By doubling the number of rescuers we notice that GET decreases, without being reduced by 2. Rescue is not a linear system and is rather a complex process. We notice also that we have similar losses and thus similar RR.

- By comparing config. 1 to config. 5: By dividing by 2 the rescue resources, we notice that GET is almost

doubled (139,4 instead of 70,9), where as the rescue rates remain close to each other.

- Config. 5 gives percentages of death and RR which are very close to those of config. 3. This may be explained by the fact that, in both cases, at start time the numbers of rescuers is close to number of alive victims and the percentages of dead victims are similar.

- For configurations 6 and 7, where 200 alive victims are set at start time, config. 6 gives lower GET and lower losses of lives than config. 7; this is explained by the number of available rescuers.

In other words, by considering the seven cases, we notice that GET values for config. 3, config. 5 and config. 6 are close to each other although the differences in victims and rescuers numbers. Similarly, GET values of config.1 and config. 2 are almost equal. This may be explained by the fact that for the former three configurations, the ratio of number of rescuers by number of victims are close to each other (almost equal to 0,5) and for the latter two configurations the ratio is the same. We notice also that the GET value is the smallest for config. 4 having the biggest ratio, and is the biggest for config. 7.

Consequently, we conclude that the GET value depends on the ratio of numbers of rescuers per victims and not on the numbers themselves: same ratio seems to give same GET.

Also, increasing the number of rescuers does not improve automatically rescue efficiency by reducing losses of lives. This conclusion assumes that there are no evolving environment factors such as fires or floods. However, increasing rescue resources improves decreasing evacuation times which is very important in case of evolving environment factors by getting victims in safer places earlier.

Config. 2 results show that early intervention on disaster site enhances rescue efficiency by reducing losses of lives, which confirms our intuition.

2nd experiment results: impact of electronic communication
Similarly to results discussed with experiment 1, we find that (see Table 3):

- Configurations 2 and 4 give better results than configuration 1 (reduced GET and reduced losses). Thus beginning rescue earlier or increasing rescue resources improve efficiency.

- Configurations 3 and 5 give worse results than configuration 1. Henceforth, increasing victims' number or reducing rescuers does not improve rescue process.

- From configurations 6 and 7 we conclude that given a great number of victims, providing more rescuers reduces losses and evacuation time. However, we still need to find out till which extent this remark is true and to find out the best thresholds of rescuers, losses and delays.

Compared to experiment 1, we notice that in all cases, and configuration by configuration, we get each time, reduced GET, reduced percentage of losses and thus better RR. Therefore, we conclude that replacing paper forms by electronic communication devices improves rescue efficiency.

Also, within this experiment set and among the two tables of results, we notice that config. 4 gives the smallest GET and the lowest ratio GET/RR. Therefore, increasing the rescuers numbers added to using electronic devices highly improves rescue efficiency.

3rd experiment results: impact of distributed decision making with traditional communication mode

By distributing the decision making among rescuers divided into the site disaster in four sub-zones, and where traditional communication via paper forms continues to be used, we notice that the rescue results (GET, RR, and GET/RR), compared to those of experiment 1, change differently according to the initial configurations. This is different from experiment 2, where for all configurations

Table 3: Summary of results for the second experiment repeated for the seven configurations

Configuration		GET	%EU	%U1	%U2	%U3	%Dead	%RR	GET/RR
Config. 1	Mean	48,80	3,7	7,5	16,7	16,2	55,9	98,02	49,79
	Std. dev.	17,08	1,1	2,3	2,9	2,9	0,9		
Config. 2	Mean	42,50	37,5	17,1	17,0	14,9	13,4	86,58	49,09
	Std. dev.	9,16	3,4	3,0	2,2	1,6	3,1		
Config. 3	Mean	96,00	4,5	8,7	18,0	12,5	56,4	97,0	99,01
	Std. dev.	18,27	1,2	1,4	2,8	3,4	0,8		
Config. 4	Mean	32,60	3,0	7,7	18,9	14,2	56,2	97,4	33,47
	Std. dev.	6,38	1,6	2,2	1,7	3,0	1,1		
Config. 5	Mean	75,4	3,6	10,0	17,7	12,9	55,9	98,0	76,92
	Std. dev.	14,92	2,2	2,8	3,4	3,5	1,3		
Config. 6	Mean	106	10,3	21,6	39,0	24,4	4,9	95,2	111,40
	Std. dev.	5,77	1,9	2,4	2,4	3,0	2,1		
Config. 7	Mean	151,5	11,1	22,9	39,4	19,5	7,2	92,8	163,25
	Std. dev.	9,79	1,7	2,0	3,7	2,0	1,7		

we have a same trend (in GET decrease) compared to experiment 1. In fact, as shown on Fig. 4., we notice that experiment 3 gives, for the first six configurations, better results than experiment 1 (lower GET) and worse value (higher GET) for configuration 7.

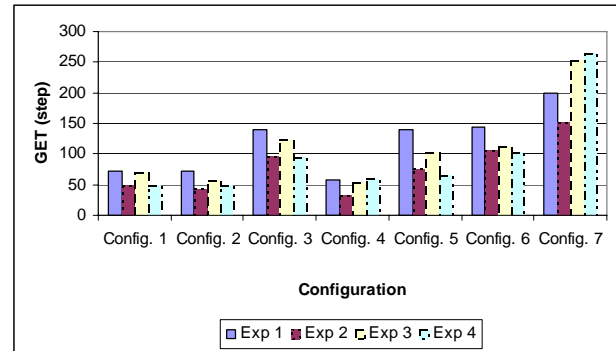


Fig. 4. Global Evacuation Time per configuration for each of the four experiments

Therefore, we can conclude that:

- Distributing decision making does not always improve rescue and depends on the initial situation properties (rescuers' and victims' numbers and states).

- Using electronic communication devices with centralized control may be more efficient than decentralizing decision making and using paper forms as in configurations 4 and 7.

4th experiment results: impact of distributed decision making and electronic communication

As shown in Fig. 4, with the configurations 1-2-3-5 and 6, combining both distribution and electronic communication (experiment 4) gives better results than experiments 1 and 3. Therefore distribution and electronic

communication scenario is better than paper communication for both strategies.

With the first configuration, experiment 4 gives the lowest GET value. With configuration 7, we notice that centralized strategies (both with electronic communication or not) give better results than distributed ones.

Consequently, distributed decision making joined to electronic communication don't improve systematically rescue efficiency. Initial situation properties play a great effect on it.

6.5 Discussion

Having made these 280 runs, our recurrent questions are "what is the best scenario at this stage?", "what are the general conclusions and findings about rescue process and its efficiency?".

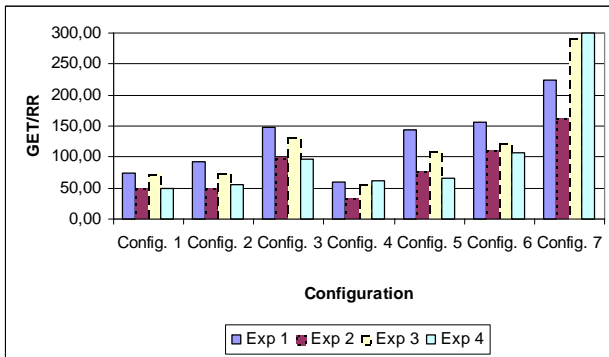


Fig. 5. GET/RR per configuration and per experiment

There is no trivial or immediate answer to such questions. In fact, basing our analysis of simulation results on GET and GET/RR criteria (see Fig. 5.), we find that, as shown in Table 4, given these configurations, the best experiment is 4 or 2, whereas the practiced one (experiment 1) ranks the last 5 times over 7.

Table 4: Ranking experiments for each configuration

Config.	Experiments			
	Rank 1 (best scenario)	Rank 2	Rank 3	Rank 4 (worst scenario)
1	Exp 4	Exp 2	Exp 3	Exp 1
2	Exp 2	Exp 4	Exp 3	Exp 1
3	Exp 4	Exp 2	Exp 3	Exp 1
4	Exp 2	Exp 3	Exp 1	Exp 4
5	Exp 4	Exp 2	Exp 3	Exp 1
6	Exp 4	Exp 2	Exp 3	Exp 1
7	Exp 2	Exp 1	Exp 3	Exp 4

More generally, we can state that:

- Given a rescue strategy and communication mode, rescue efficiency is affected by beginning rescue time, rescue resources and victims' number.

- Using electronic communication devices is better than traditional paper forms and reduces rescue delays, both with centralized and distributed decision making

strategies (experiment 1 vs. experiment 2 and experiment 3 vs. experiment 4);

- In case of using paper forms (experiment 3 vs. experiment 1), distribution may improve slightly rescue results. However, In configuration 7 where victims are much more than rescuers, distribution has a negative effect;

- In case of electronic communication (experiment 2 vs. experiment 4), centralized strategy gives similar results to distributed one, or even far better results when rescuers are too much fewer than victims (as in configuration 7) or rescuers are much more than victims (as in config. 4);

- Combining both distribution and electronic communication does not have greater effect on efficiency than using electronic communication only.

- Electronic communication has greater effect on rescue efficiency than distribution.

Finally, we can state that there is no unique "best" rescue scenario and this depends on the disaster configuration. Also, for a given configuration, it is hard to predict which would be the best.

We check by virtual simulations here that the rescue process is far from being a deterministic, nor a simple system. It is rather a complex one where the number of involved victims and their states, as well as the rescuers, their number and missions, added to their organization and interaction mode impact differently on the whole rescue process.

7. CONCLUSION AND PERSPECTIVES

In this paper, we investigated how agent-based computer simulation approach can benefit designing rescue collaborative plans. This domain is studied as a complex socio-technical collaborative system. Therefore, we have presented an agent-based approach which aims to model the dynamics of large scale crisis situations and which could be used to evaluate alternative rescue plans. We applied this approach iteratively, guided by field works, to understand the process and to design new efficient rescue organization including new collaborative technologies by means of the generic simulator. Therefore we show that we can create a virtual environment with cooperating agents interacting in a dynamic environment. Within modeling activities we can begin to understand in depth the cooperation processes, and we can find out the parameters, variables, and strategies hidden in this work.

First experimentation with the model raised interesting points. In particular, considering the difference between centralized and distributed control and the difference between the communications based on paper or electronic forms, as well as the impact of numbers and states of victims and numbers of rescuers.

Our future work in this application field can be continued as two kinds of activities: First, immediate research activities would use this simulator in-depth by designing and running further hypothetical experiments in order to explore all the simulator cases; we may assess, among others, the impact of dividing the side into sub-zones, the

impact of first rescuers exploration and its strategies, the impact of search strategy, the impact of locations of AMP and/or rescuers and their repartition/concentration on some areas, the alternative rescue behavior, impact of AMP location. We need also to check our general results and conclusions with really large scale rescue involving hundreds and thousands of victims and rescuers.

Second, we plan to incrementally build more complete and realistic model versions to focus on dynamic environment properties such as fire evolution, route blocking or traffic jams. Hence, new heuristics need to be implemented and assessed. To be more realistic and in order to be able to simulate real accidents with real map, we are working on the connection of the simulator to a GIS.

Validation remains a key and complex issue which needs to be kept as an on going task.

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