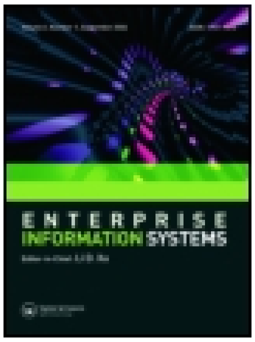

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Modelling and simulating a crisis management system: an organisational perspective

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ABSTRACT

Crises are complex situations due to the dynamism of the environment, its unpredictability and the complexity of the interactions among several different and autonomous involved organisations. In such a context, establishing an organisational view as well as structuring organisations' communications and their functioning is a crucial requirement. In this article, we propose a multi-agent organisational model (OM) to abstract, simulate and analyse a crisis management system (CMS). The objective is to evaluate the CMS from an organisational view, to assess its strength as well as its weakness and to provide deciders with some recommendations for a more flexible and reactive CMS. The proposed OM is illustrated through a real case study: a snowstorm in a Tunisian region. More precisely, we made the following contribution: firstly, we provide an environmental model that identifies the concepts involved in the crisis. Then, we define a role model that copes with the involved actors. In addition, we specify the organisational structure and the interaction model that rule communications and structure actors' functioning. Those models, built following the GAIA methodology, abstract the CMS from an organisational perspective. Finally, we implemented a customisable multi-agent simulator based on the Janus platform to analyse, through several performed simulations, the organisational model.

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Crisis management; multi-agent system; organisation; simulation

1. Introduction

The rapid development of economy and society in addition to abnormal changes of the environmental conditions (ozone depletion, global warming, loss of freshwater, etc.) make modern crises more and more frequent. Moreover, the inherent vulnerabilities of modernisation (pollution, industry development, epidemics, etc.) (Qing, Huimin, and Yanling 2012; Chung, Ip, and Chan 2009) increase their severity, cost and aftermath.

Generally, disasters can be man-made such as nuclear accident (Fukushima, 2011) and chemical attack (Syria, 2013) or natural such as tsunami (Asia, 2004), flood (Thailand, 2011), earthquake (Haiti, 2010), etc. Disasters can strike anytime and anywhere. They are extremely harmful since they threaten people's lives causing deaths, injuries, diseases, etc. and heavily affect the economy. These events' impacts are more devastating in developing countries due to poor housing construction, lack of technologies and resources and the non-existence of a disaster preparedness culture.

The crisis management is defined as the process by which an organisation deals with a major unpredictable event that threatens to harm the organisation or the whole society (Aldewereld et al.

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2011). Dealing with such events requires quick intervention in order to reduce damages, save people's lives and preserve the environment and the economy.

All crises are commonly characterised by their dynamics due to their evolution over time, unpredictability in most of the cases and the heterogeneity of the involved actors. In fact, crisis management systems engage several emergency actors attached to various organisations (police, medics, army, etc.). These organisations have different skills and missions to achieve. Their tasks are strongly correlated and therefore need to be coordinated. Hence, organisations have to interact frequently and cooperate at a high level to deal with the crisis. As a result, the efficiency of the crisis management system depends on the communication among organisations and stakeholders. Thus, structuring organisations' communications and their functioning is a crucial requirement. Without a structural regulation, interactions can become numerous, costly and unpredictable which may lead to a chaotic collective behaviour and to the paralysis of the crisis management process.

In this context, agent technology allows abstracting, modelling, simulating and analysing complex systems with an organisational perspective. Indeed, an agent is known to be an appropriate paradigm to build autonomous, reactive and proactive software components able to communicate with sophisticated languages and protocols. Agents also provide high-level organisational concepts (groups, roles, commitments, interaction protocols) allowing abstraction of a system with macro and social concepts (roles, interaction protocols, groups). As a result, multi-agent systems (MASs) are suitable for developing complex applications that can be naturally modelled as societies of autonomous interacting entities such as crisis management systems.

Following this view, this article adopts an agent-based organisational perspective to design and simulate a crisis management system (CMS). The objective is to abstract the CMS from an organisational perspective and to evaluate it. In fact, this perspective constitutes a design support since it makes possible to apprehend and to structure a MAS through various roles and their interactions. Furthermore, it structures the MAS execution by defining behavioural and interaction rules to which agents must conform. As a result, modelling, simulating and evaluating the CMS from an organisational view are crucial requirements.

The contribution of this article is the *design, simulation and evaluation of a multi-agent organisational model* that represents the management system of a particular emergency situation: a snowstorm. The objective is to assess the efficiency of the crisis management system and to emphasise its strengths as well as its weaknesses. In this perspective, we have applied the GAIA methodology (Zambonelli, Jennings, and Wooldridge 2003) for the analysis and the design of the model as well as the Janus platform (Gaud et al. 2008) for its implementation. More precisely, our contributions are threefold:

- A *conceptual model of the snowstorm emergency environment*. This model represents an abstraction of the emergency situation in which the concepts, their properties, and their relations are identified. This model serves a base for our multi-agent design and for the definition of simulation's parameters.
- A *multi-agent organisational model for the snowstorm crisis management system* that identifies the roles involved in the system, the links that exist among them and the organisational patterns that structures their interactions.
- An *implementation of a multi-agent based snowstorm simulator and an evaluation of the considered model*. Our evaluation measures performance criteria related to the crisis management time, the number of exchanged messages, etc.

The remainder of this article is organised as follows. In Section 2, we review the related work. In Section 3, we introduce our case study: Ain Draham snowstorm. Then, we specify our multi-agent organisational model: the environment, the roles, the organisational structure and interactions model in Section 4. We describe, in Section 5, our multi-agent based snowstorm disaster simulator used to evaluate our model experimentally. Simulations scenarios and the obtained results are presented in Section 6. Finally, we summarise and lay out the future work.

2. State of the art

The increasing frequency of crises and the growing of disasters' impact claim a continuous evolution of the response strategies in order to manage crises and reduce losses.

Based on their prior experiences, governments have developed several emergency plans and response behaviours (Lachtar and Garbolino 2012). Moreover, the emergence of new technologies provides the ability to afford new challenges and perform tasks rapidly and effectively. In this context, crisis management is more and more developed using new technologies (computed simulations, decision support systems, real time monitoring systems, etc.). Crisis management system (CMS) plays a vital role in today's disaster management (Neuhaus et al. 2012). In fact, in emergency situations, operators have to rapidly deal with the disaster and apply the most suitable remedial actions to reduce damages. However, due to the high time pressure, the large volume of data, the escalation of stakeholders' number, actors may not be able to respond adequately to critical conditions (Negnevitsky 2008). Wrong decisions and actions can inhibit the response process and engrave the situation. In order to ensure the efficiency of crisis management, computational CMS is widely used in several disaster management functions such as communication (Perry, Taylor, and Doerfel 2003), data collection (Reddy et al. 2009), resources management (Gaba et al. 2001), simulation (Steadman et al. 2006; Hawe et al. 2011), decision support (Asuncin, Garcaprez, and Palao 2004), information mediation (Bénaben et al. 2008), etc.

In this context, multi-agent system (MAS) has been recognised as a powerful tool that allows designing and running controlled experiments which helps deciders to assess, test and optimise response strategies. As a result, several multi-agent based simulators have been proposed for designing and testing crisis management techniques. Those simulators can be used to reproduce the behaviour of the different components of the crisis management system (individuals, actors, organisations), to evaluate the different crises scenarios and to optimise the intervention plans. For instance, the Modular OpenRobots Simulation Engine (Garcıa-Magarino, Gutiérrez, and Fuentes-Fernández 2008) has been developed based on scenarios proposed by the RObots et Systèmes Auto-adaptatifs Communicants Embarqués (Garcıa-Magarino, Gutiérrez, and Fuentes-Fernández 2008) project for fire fighting. In addition, the (Simulation of the Tactical and Operational Response to Major Incident (STORMI) simulation environment (Hawe et al. 2012) has been developed to test the existing emergency plans in the United Kingdom and to evaluate new proposed plans. STORMI is a part of a project that aims to identify how to respond adequately to major incidents in the United Kingdom. Other simulators have been developed to observe people's behaviours during disasters such as the simulators proposed in (Van Truong et al. 2013; Belhaj, Kebair, and Said 2014). In addition to those simulators, researchers and crisis management experts have worked on multi-agent platforms aiming to provide a generic simulation environment such as Cormas (Le Page et al. 2000) and RoboCupe Rescue (Kitano 2000). Cormas (Common-pool Resources and Multi-agent Systems) has been developed to provide a multi-agent framework to simulate the interactions between a group of agents and a shared environment holding natural resources. RoboCup Rescue platform provides a complete simulator for large-scale urban disaster scenarios (fire, earthquake, flood, etc.). Both platforms can be used for simulating any emergency situation. MAS has also been used to support decision making during crisis management by providing realistic plans of action (Markatos et al. 2007; Asghar, Alahakoon, and Churilov 2006; Zerger and Smith 2003). Communications among involved organisations as well as heterogeneous information mediation and collaborative process in crisis management systems have also been investigated using MAS (Bénaben et al. 2008; Le et al. 2013).

Giving this context, much work has been developed to design and simulate CMS. However, they remain at low-level and do not consider the organisational aspect. Here, we argue that considering the crisis management system at a macro level, through structuring organisations and interactions, is important and realistic. The organisational aspect (Ferber, Gutknecht, and Michel 2004; Dignum 2009) has been considered in several systems such as (Aldewereld et al. 2011; Quillinan et al. 2009;

Gonzalez 2010) in order to reflect the environment change and the dynamic behaviour of its components. For instance, the ALIVE project (Quillinan et al. 2009) aims to apply organisational theory to design and implement CMS. Moreover, the importance of organising MAS and the impact of organisational structures on the efficiency of the crisis management system have been proven in their work (Aldewereld et al. 2011). More precisely, authors show, using graph theory measures (Grossi et al. 2006), that the structural aspect and the organisation topology (hierarchical, decentralised, etc.) highly affect the CMS's efficiency.

In this perspective, the objective of our work is to model a particular CMS in order to assess its efficiency and its weakness from an organisational view.

3. Case study: Ain Draham snowstorm

In this section, we firstly introduce our case study: a snowstorm disaster. Secondly, we give an overview of the involved organisations and their interactions.

In recent years, Ain Draham, a mountainous city of the governorate of Jendouba in north-western Tunisia, has been more and more facing rude snowstorm catastrophes. This city is built at an altitude of 800 metres with a very poor infrastructure. Every year, in winter time, Ain Draham goes through heavy snowstorms. Those disasters usually cause the interruption of essential vital services such as water, electricity and transportation networks making extremely difficult all rescue operations. To make matters worse, snow melts weeks after the snowfall which causes, most of the times, flooding and landslides. The nearby dams frequently overload and flood many surrounding areas.

For instance, during February 2012, the city has been hit by the most intense snowstorm in the Tunisian climate history. Back then, snow depth reached 1.7 metre and, in addition to the previously mentioned damages, some buildings collapsed under snow weight causing severe injured and homeless people. Rescue authorities were not prepared to such natural catastrophe and took four days to react efficiently.

In this context, it is important to notice that Tunisia is known for its moderate climate and non-adapted infrastructures to such extreme conditions. The government used to deal only with traditional disasters such as drought, flooding, forest fire, etc.

This crisis has been managed by several authorities and organisations namely: the Army, the National Guard, the Medical Staff, the Civil Protection and the Civic Organisation. Figure 1 illustrates the mentioned organisations and their communications for the crisis handling process.

In Figure 1, we presented the several involved organisations (Army, Medical Staff, Civil Protection, etc.) in the crisis management process. These organisations must interact among

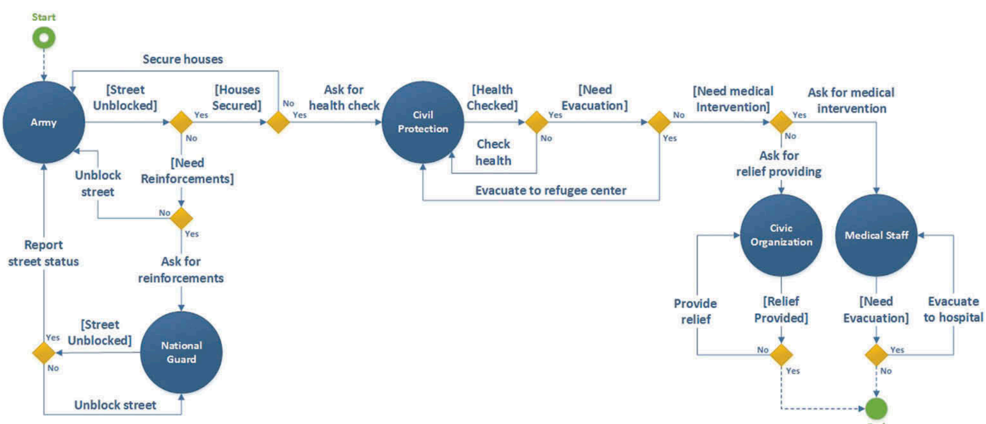

Figure 1. Inter-organisational communications for snowstorm emergency.

each other in order to handle the disaster and reduce its impact. Thus, the unidirectional arrows, presented in this schema, illustrate the inter-organisational interactions (Secure houses, Ask for health check, Evacuate to hospital, etc.). Since we consider a dynamic crisis environment, we established many conditions to be verified before undertaking any action or interaction. These conditions are illustrated through the orange squares in the diagram ([Need Reinforcements], [Health Checked], [Need Evacuation], etc.). In order, to understand the sequence of interactions and actions, it is important to follow the arrows' directions and to check the conditions each time.

The disaster tackling starts with a discovery task ensured by the Army in order to detect primary damages. Based on findings, the Army deploys needed resources to unblock and secure streets. When reinforcements are needed, the National Guard may support the Army in its mission for roads unblocking. Once streets cleared, the Army secures harmed houses in order to prevent collapsing and protect inhabitants. The Civil Protection may then intervene to check inhabitants' health status and evacuate them to refugee centres if they are in danger. People with grave health situation are cared by the Medical Staff and evacuated to hospitals if needed. Finally, the Civic Organisation provides inhabitants with needed reliefs such as food, covers, etc.

It is worth noting that the facts mentioned above were extracted through several meeting held with the civil protection authority heads as well as deep investigation on press reviews and reports published after the considered disaster.

4. Overview of the organisational model for crisis management

In this section, we propose a multi-agent organisational model of the considered CMS. More precisely, we build several interacting models based on a deep investigation of the domain (Bénaben et al. 2008) as well as press reviews and interviews with the involved stakeholders. These models are: the environment, the role, the organisational and the interaction models. Each one represents an overview of the system from a specific perspective. We proposed in our previous work (Thabet, Chaawa, and Said 2014) preliminary environment and role models. These two models are refined in this article while we newly propose the organisational and the interaction models. In this perspective, several organisational methodologies such as GAIA (Zambonelli, Jennings, and Wooldridge 2003), AALAADIN (Ferber and Gutknecht 1998) and MOISE+ (Hübner et al. 2010) are useful to guide the analysis and the design of these models. In our work, we follow the widely used GAIA methodology that offers a conceptual tool including notations and models to guide the analysis and the design of MAS with an organisational perspective. In fact, this methodology is known to be appropriate for the development of systems with static organisational structure (relationships among agents do not change at runtime) and agent's abilities (provided services do not change at runtime) and is therefore compliant with the characteristics of our CMS.

4.1. *Snowstorm environmental model*

In this section, we describe the crisis environment. In GAIA, the environment model is an abstraction of the context in which evolve the actors. In our case, the environment model includes the concepts involved in the snowstorm disaster and the relations among them. The environment model, depicted in Figure 2, is represented using UML (Unified Modelling Language) notation (Rumbaugh, Jacobson, and Booch 2004). This model is considered according to two aspects. The first one defines the harmed goods and infrastructures. The second aspect defines the resources used to handle the situation. The identified entities are referenced geographically by mark points. Information about the region, the delegation and the city where they are situated are also recorded.

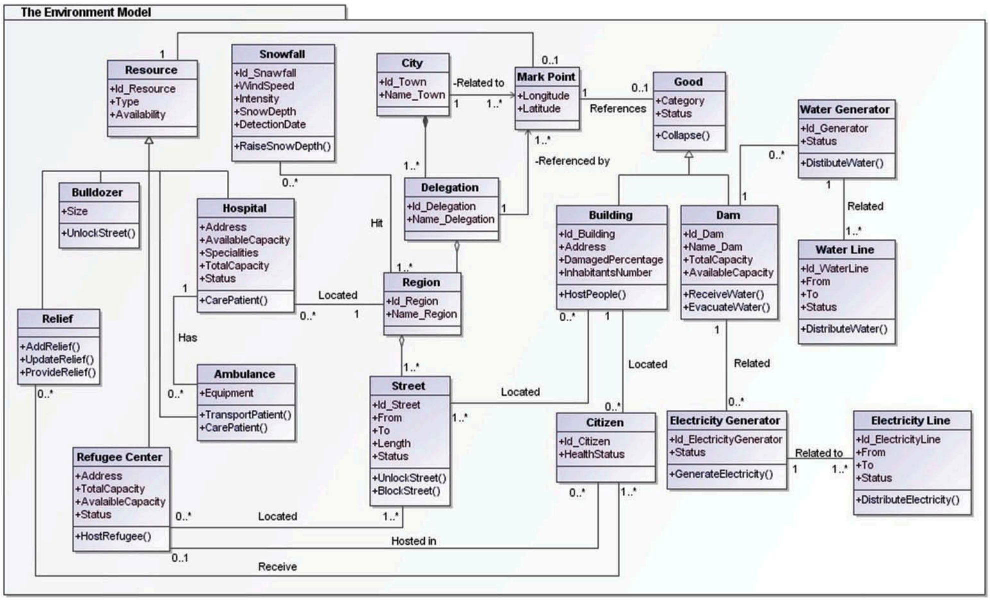

Figure 2. The environmental model.

The most important concepts of this model are:

- *Snowfall*. This entity records information about the local conditions such as the measurement of snow depth, storm intensity and wind speed. These properties change over time. They define the disaster gravity and therefore the amount and nature of needed interventions.
- *Resource*. Resources are required to deal with the disaster. In our case, the resource can be a snowplough to remove snow and clear streets, an ambulance for first aid and victim's transportation, a hospital where victims receive treatments, etc. Resources have static and dynamic characteristics. Static characteristics are about the type, the quantity, the nature, etc. Dynamic characteristics concern information that can evolve over time such as the capacity of a hospital or a refugee's canter, the equipment availabilities, etc.
- *Street*. Represents the region's streets that are cleared and secured during the disaster response.
- *Building*. Represents the region's buildings. They host inhabitants. Those buildings may be in danger situation and risk to collapse.
- *Citizen*. It concerns all affected persons during the catastrophe. These persons are located in buildings and can be transported to hospitals or refugee's centres.

4.2. *Snowstorm emergency role model*

In this section, we introduce the roles involved in the considered crisis management system. In GAIA, a role is the representation of an agent functions and responsibilities. An agent may play one or many roles at the same time. Roles are represented in the GAIA methodology through their permissions and responsibilities (Zambonelli, Jennings, and Wooldridge 2003). In the first hand, permissions define the resources accessibility by roles. In our model, the resources that we defined in the previous model are accessible by all roles. In the other hand, responsibilities represent both the internal actions that a role can perform and the protocols that require interaction with other

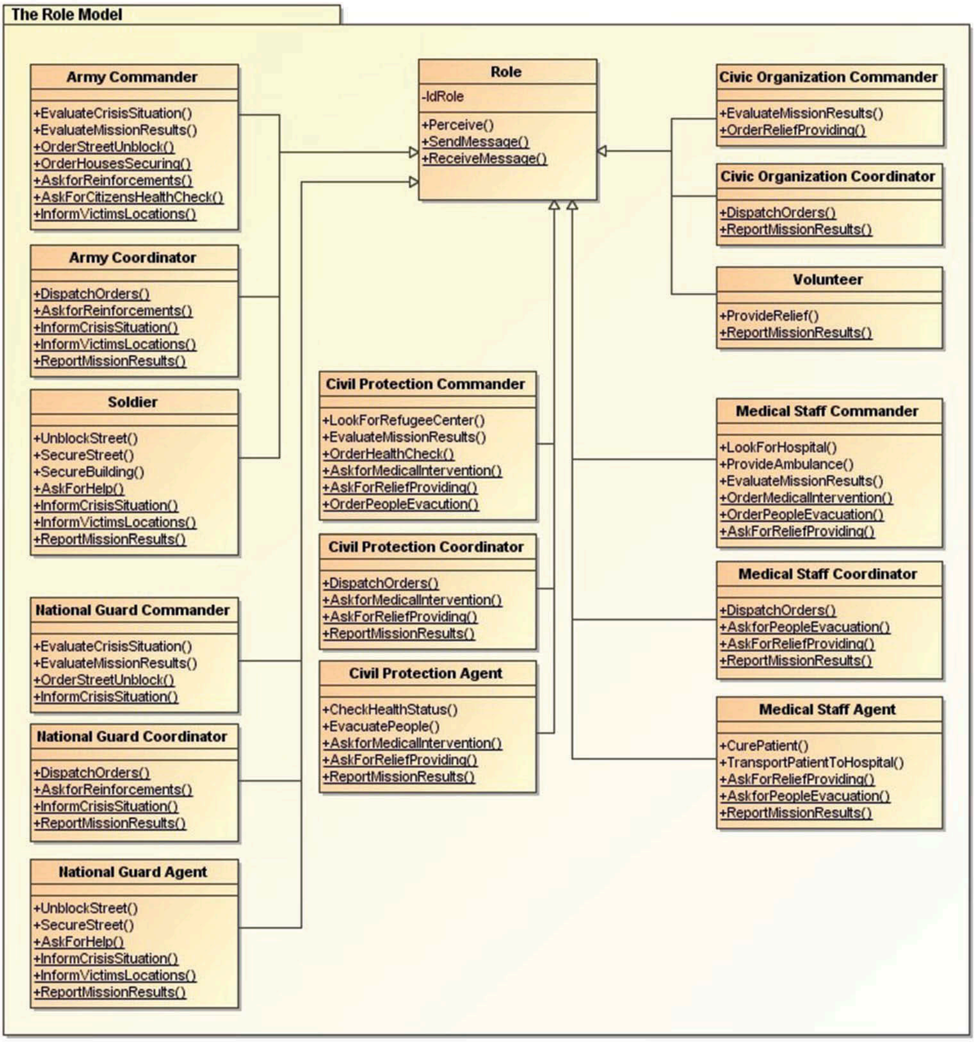

Figure 3. The role model.

roles. We represent respectively responsibilities and protocols as operations and underlined operations in the class diagram of Figure 3.

Our work focuses on organising the executing system functioning. This system is responsible for clearing streets, securing unsafe streets and buildings, providing citizens with reliefs, evacuating them from stricken areas to refugee's centres or hospitals and giving medical treatments to injured people. These specific use cases assume the intervention of the organisations introduced in the case study: the Army, the Civil Protection, the National Guard, the Civic Organisation and the Medical Staff. Each organisation is composed of three roles namely: Commander, Coordinator and Agent (Worker). Commanders lead their organisations by taking strategic decisions and order coordinators to ensure their execution. They also handle communications among each other in order to ensure inter-organisational coordination. Coordinators are communication facilitators among agents and their corresponding commanders. In practice, they are responsible of dispatching received orders from commanders to the adequate agents. They also filter incoming requests and information from agents then forward it to their commanders. Finally, workers execute actions and operations on the field in order to handle the disaster.

The identified roles with their responsibilities represented as operations are depicted in the following diagram. Interactions will be detailed in the next section.

4.3. *Snowstorm emergency organisational structure and interactions model*

In this section, we present the organisational structure of our CMS. Furthermore, we describe interactions among actors through an interaction model. It is important to notice that the built models cope with the real CMS functioning and structure. Our objective is to simulate the currently used organisational based CMS in order to evaluate its benefits and drawbacks.

At first hand, the organisational structure enables the definition of roles, their responsibilities and permissions in addition to the interactions rules among them. It structures organisations internally and also regulates the inter-organisational cooperation in order to achieve their common goal.

In our case, each organisation is structured hierarchically which means that workers actions must be approved or ordered by their superiors. Furthermore, each message must go through the entire hierarchy to reach its destination. For instance, each commander can only interact with his coordinators who have to transmit in their turn received messages to their available workers.

Otherwise, the inter-organisational communications are only ensured through commanders' interactions. In this context, it is important to notice that these interactions are made according to the previously introduced inter-organisational communications for a snowstorm emergency (Figure 1). For instance, the Army commander, the National Guard commander and the Civil Protection commander can interact with each other to remove the snow and check the citizens' health status. The Civil Protection commander, the Medical Staff commander and the Civic Organisation Commander may inter-communicate in order to cure people and transport them to hospitals and refugee centres, etc. This organisational structure is illustrated in Figure 4.

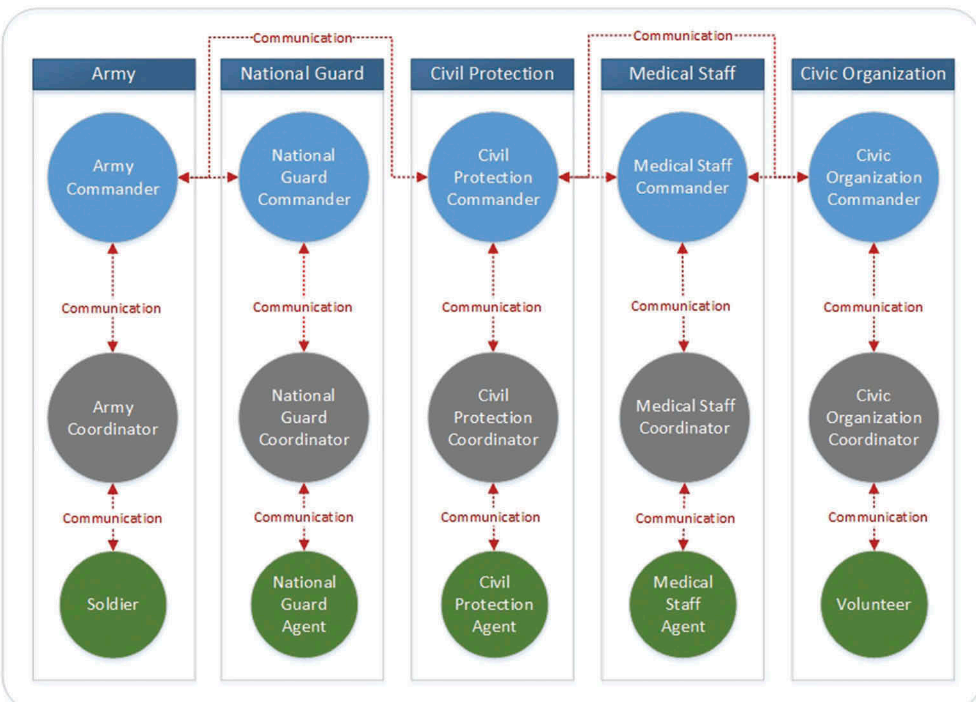

Figure 4. The organisational structure and inter-organisational communication.

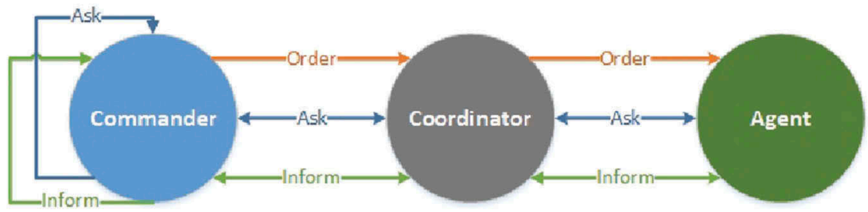

Figure 5. The interaction model.

At a second hand, the involved actors need to interact frequently following several interaction rules. The interaction model describes the relationship among roles through protocols. In our model (Figure 5), roles perform three types of protocols: Inform, Ask and Order. More precisely, the Inform protocol represents an information exchange where an initiator intend to inform its receiver and do not wait for a feedback. The Ask protocol contains a request that may be accepted or refused by the receiver and thus a response message must be sent back. Finally, the Order protocol is emitted by an initiator and it require an immediate execution by the receiver. The following figure represents an abstraction of interactions among the different roles.

5. Implementation

We have implemented a multi-agent organisational snowstorm crisis management simulator in order to validate and evaluate our model. In this context, several multi-agent simulation platforms can be used such as GAMA (Drogoul et al. 2013), NetLogo (Wilensky and Evanston 1999), Janus platform (Gaud et al. 2008), etc. Our proposed simulator is developed based on Janus platform. Janus provides a comprehensive set of features to develop, run, display and monitor multi-agent organisational based applications using Java. It can be used as an agent-oriented or an organisational platform unlike the GAMA platform that mainly focuses on the spatial simulation aspect and the NetLogo that does not consider the organisational aspect.

The architecture of our simulator is illustrated in Figure 6. It includes an input GUI, a kernel and an output GUI.

This simulator allows users to enter simulation parameters through the input GUI. Then, the kernel generates corresponding agents and simulates their functioning, organisation and interaction based on our organisational model. Finally, simulation results are displayed through the output GUI.

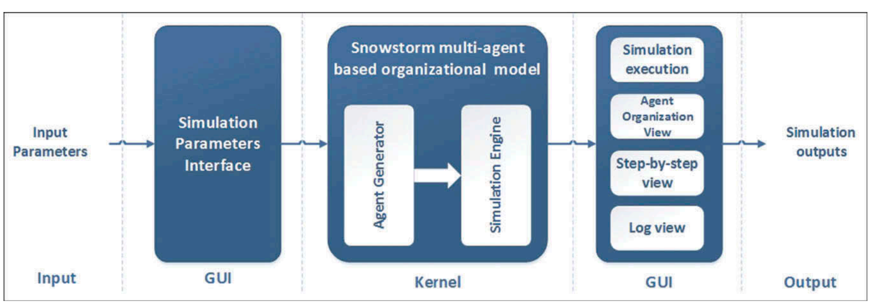

Figure 6. The multi-agent based organisational simulator architecture.

5.1. *Input GUI*

Our simulator provides the following input GUI illustrated in Figure 7.

Our input GUI allows users to enter parameters related to the environment and to the emergency system. It is important to notice that these parameters are defined accordingly to the environment model. Those parameters are classified in three groups: disaster's parameters, impacted system parameters and emergency system parameters. Firstly, disaster's parameters define

- the *number of regions* affected by the snowstorm,
- the *minimum initial snow depth* represents the depth of the snow when the disaster strikes and it is measured in metre,
- the *minimum initial intensity of the snowfall* that defines the snowstorm severity,
- and *the minimum initial wind speed* measured in km/h.

Secondly, the impacted system parameters specify

- the *population* existing in the stricken area,
- the *minimum initial health status* which defines the minimum health status indicator that a citizen may have just before the disaster strikes. This indicator is between 0, if the citizen is dead, and 1 if the citizen is completely healthy,
- the *number of houses*,
- and *the minimum initial house status* defines the minimum initial property status that a house may have before it is affected by the disaster.

Finally, the emergency system parameters define the number of workers involved in the crisis tackling for each organisation (number of soldiers, number of civil protection workers, number of volunteers of civic organisation, etc.) in addition to the available resources numbers (number of hospitals, number of refugee centres, number of snowplows, etc.).

It is worth noting that the initial simulation parameters values are generated randomly and do not fall below the minimum entered values. The objective is to create diversity over snowfall

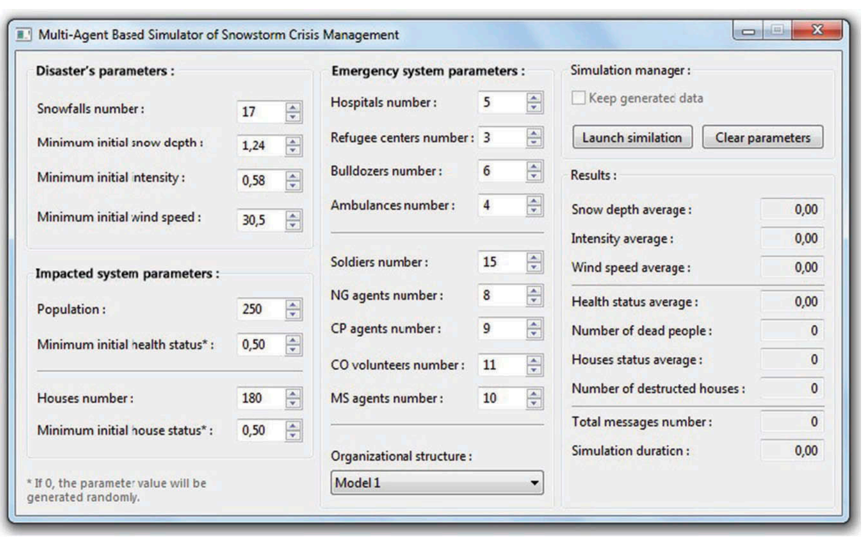

Figure 7. Screenshot of the multi-agent organisational simulator input GUI.

regions while ensuring obtaining a particular disaster gravity. Furthermore, the defined parameters are strongly correlated and evolve during the catastrophe. Practically, the snowstorm intensity and the wind speed evolve randomly during the simulation, which will affect the snow depth evolution and hence houses status and inhabitants' health.

5.2. *Kernel*

The kernel has two roles. Firstly, it generates the environment components based on entered parameters. These components are very dynamic and keep evolving during the simulation. The kernel also generates the organisational structure with the corresponding roles according to entered data. The generated organisations' functioning and interactions are performed according to our previously defined models. Secondly, the kernel launches the simulation execution and computes results when the simulation ends.

5.3. *Output GUI*

Once a simulation is completed, several dashboards and a log file are generated. The dashboards show the evolution of various performance metrics over time such as the number of messages, snow depth, citizens' health status, etc. While, the log file traces all interactions among actors (initiator, receiver, type, etc.). Those outputs may be used by analysts to study the system behaviour.

6. Experimentation and results

In this section, we define series of input parameters in order to run simulations. The objective is to validate and evaluate the proposed model using several performance metrics. More precisely, our experiments were designed in order to study the impact of the organisational structure on crisis management.

In this context, each simulation is run with a population of 1000 citizens with a minimum health status of 0.7 and 650 houses with a minimum status of 0.6. We also define three levels of the disaster and emergency systems and their corresponding values. The defined levels and values are specified through the Tables 1 and 2. These values are based on previous recorded incidents (Ain Draham snowstorm in 2012, Tataouine floods in 1995, Nahli Parc wildfire in 2014, etc.). These values have been reviewed and confirmed by the response authorities.

Table 1. Disaster's parameters.

	Heavy	Medium	Soft
Snowfalls number	30	15	5
Minimum initial snow depth (m)	1.2	0.6	0.3
Minimum initial intensity of the snowfall	0.8	0.5	0.3
Minimum initial wind speed (km/h)	70	50	20

Table 2. Emergency system parameters.

	Huge	Medium	Limited
Hospitals	8	3	1
Refugee centres	16	6	2
Snowplough	34	10	5
Ambulance	18	8	2
Soldiers	50	25	5
National Guard agents	40	20	3
Civil Protection agents	45	21	6
Medical Staff agents	35	17	5
Civic Organisation volunteers	30	18	10

Based on these settings, we perform nine simulation scenarios representing all possible combinations of the defined systems' levels. In this article, we consider four performance metrics that are: simulation time, number of exchanged messages, snow depth evolution and exchanged messages evolution. It is worth noting that our work focuses on the impact of the organisational structure on the efficiency of the crisis management. Thus, we consider this aspect's related metrics to emphasise the changes of the system's behaviour in the different scenarios.

Figure 8 illustrates the simulation duration for each executed scenario. The simulation duration measures the time needed by the emergency system to handle the situation. The simulation stops when harmed houses are secured and endangered citizens are cared (cured, transported to hospitals or refugee centres, etc.).

The given results show that the simulation duration is very sensitive to the variation of the emergency system size and the disaster gravity. In fact, the more the event is heavy and the emergency system is limited the more the handling time is long. For a same disaster configuration, a huge emergency system is able to respond to the catastrophe in a short time contrariwise a limited system takes almost triple time due to the lack of resources and workers. For instance, in a heavy snowstorm, the huge system takes 640 ms and the limited system took 2200 ms (2.2 seconds) to respond to the crisis. For a same emergency system configuration, the simulation duration changes from a disaster level to another for example a medium system takes respectively 1180, 1020 and 200 ms for the heavy, medium and soft snowstorms. To summarise, the simulation time escalates when the disaster increases or the emergency system shrinks.

Figure 9 illustrates the number of exchanged messages during the simulations.

The results show that the limited emergency system generates the highest amounts of messages during the catastrophe handling. In fact, the limited number of workers and the lack of resources impose a massive interaction to respond to the crisis. Workers have to frequently send messages to ask their superiors for reinforcements. These messages must go through the entire hierarchy which highly increases their total number. In a heavy snowstorm circumstance, huge and medium emergency systems produce a nearby amount of messages to the limited system. Indeed, crucial situations require a high level of interaction and hence enormous volume of messages is generated.

In the following illustrations (Figures 10 and 11), we monitor the snow depth and the number of exchanged messages during the first 300 ms of the disaster lifetime.

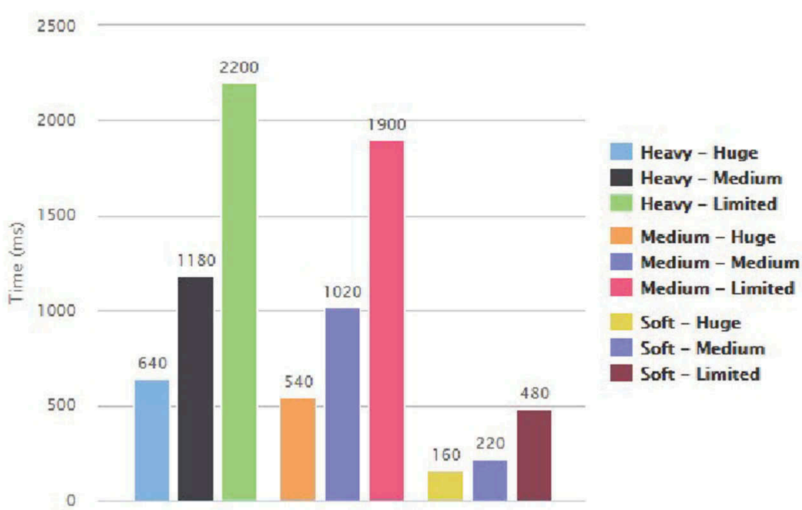

Figure 8. Simulation time.

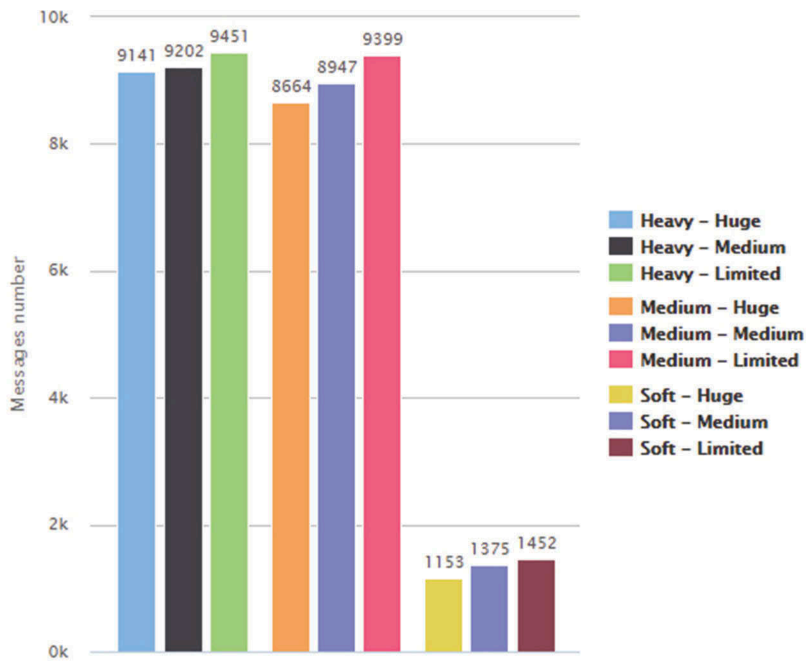

Figure 9. Number of exchanged messages.

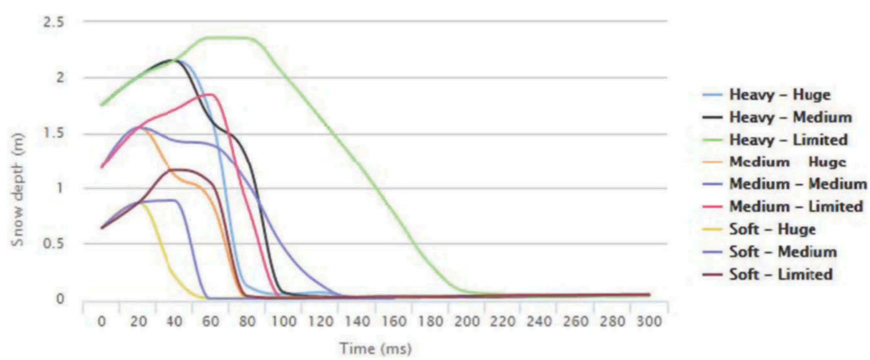

Figure 10. Snow depth evolution over 300 ms.

Our hierarchical emergency systems take time to start their operations to clear streets and remove snow. In fact, this delay is explained by the fact that each operation must be revised and approved by the leaders. Moreover, the speed of snow removal depends on the emergency system size. In fact, the huge system is able to remove the snow rapidly thanks to the availability of workers and resources. For instance, this system reduces the snow depth from 1.5 m to 0 in 60 ms for a medium catastrophe. The limited system takes too much time to start responding to the disaster and its intervention does not affect the situation rapidly.

The given results show that the messages number rise when workers start their activities on the ground. In fact, at this phase, workers are continuously interacting with their superiors to ask for help or to keep them up to date. Generally, exchange rate reaches its maximum after the end of snow removal mission. Indeed, when streets are cleared, several organisations start interacting in a rush and at the same time in order to save people lives and reduce damages.

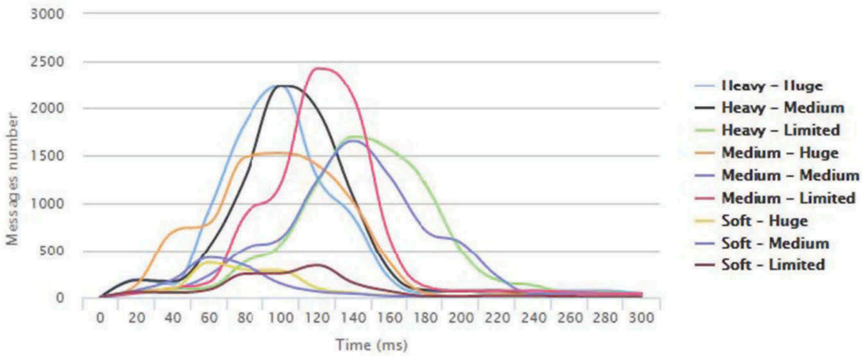

Figure 11. Exchanged messages evolution over 300 ms.

The obtained results show that limited systems generate a high amount of messages and take too much time to handle the crisis. Contrariwise, the huge emergency system tackles the disaster rapidly with less messages. However, when the crisis escalates, medium and huge emergency systems generate a nearby amount of messages which means that even those systems may be inhibited in a large scale disaster.

7. Conclusion

Crises are complex situations made of several interacting heterogeneous, distributed and autonomous organisations evolving in an unpredictable and dynamic environment. These organisations have to interact and cooperate frequently in order to manage the crisis efficiently. Without a structural regulation, these interactions can become numerous, costly and unpredictable and therefore lead to a chaotic collective behaviour. This article deals with the modelling, simulation and the experimental evaluation of a crisis management system considering an organisational perspective. In fact, the organisational approach provides the advantages of abstracting a system at a high level with macro and social concepts (roles, interaction protocols, groups) and allows the easy design and implementation of open and dynamic systems such as crisis. Thereby, abstracting, simulating and evaluating the CMS from an organisational view is a crucial requirement. The final objective of this work is to help deciders to understand the past and better plan the future for a better management of such situations.

More precisely, we have proposed a multi-agent organisational model (OM) for a snowstorm emergency management. The established model copes with the real deployed crisis management system in order to assess its strength as well as its weakness. In fact, we held several meetings with the civil protection authority heads which guided us through the design of the considered model. The proposed model has been validated: it has been implemented and its performance has been discussed. We have evaluated several performance criteria with different disaster levels and with different emergency response systems sizes. The used experimentations data have been also provided by the response authorities in order to ensure the accuracy of the obtained experimental results. According to our implementation, we have shown that the hierarchical structure of our model generates a high volume of messages when the crisis escalates and the emergency system may be inhibited in a large catastrophe. This issue will be considered in future research. However, our OM presents several qualitative advantages including:

- *Modelling and simulating a real word application*. Our OM is proposed in order to model and simulate snowstorm crisis management in the region of Ain Draham. The simulator represents adequately the disaster environment, the OM's functioning and structure and measures several performance criteria related to the CMS's performance.

- *Simulation and recommendations*. Our simulator can be used to run experiments with different scenarios in order to help decision makers to be prepared to such situations, to tune the proposed CMS from an organisational view in order make it more flexible and reactive. The simulator can also be used to establish well defined management plans, to evaluate the defined plans and to optimise their response strategies.
- *Dynamic and open system*. Our OM abstracts and simulates open and dynamic systems. Crisis environment is most of the time dynamic and evolves in an unpredictable way. Several organisations under the auspice of different authorities are involved. The more the disaster increases, the more the number of involved organisations increases as well. The participants are also dynamic as people can join and leave organisations. The organisational model is well adapted for such context since organisations are active entities that can be able to reorganise dynamically and to adapt to the environment changes. Moreover, the use of an organisational perspective eases openness: agents playing predefined roles can enter or leave the crisis management system freely.

This work opens a number of issues for future research. The first issue we are currently investigating is related to the proposal of a more flexible emergency system through the enhancement of its organisational structure. For this purpose, simulations with different organisational structures (with a centralised coordinator, completely distributed, etc.) and various snowstorm disaster scenarios will be realised. The objective is to compare the impact of organisational structures on crisis management effectiveness. The second issue is related to the structural evaluation of the different organisational models. Structural evaluation concerns the communication topology of the organisation and can be based on Grossi's framework (Grossi et al. 2006). The objective is to evaluate the design of the different OM and proof organisational qualities such as the flexibility (the capacity to adapt easily to changing circumstances), the robustness (how stable the organisation is in the case of anticipated risks) and the efficiency (the amount of resources used to perform its tasks). Finally, a comparison of our OM with other approaches can be made in order to prove its efficiency.

Disclosure statement

No potential conflict of interest was reported by the authors.

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