Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

A HYBRID APPROACH TO STUDY COMMUNICATION IN EMERGENCY PLANS

Cristina Ruiz-Martin [+,*]
Gabriel Wainer [*]
[*]Department of Systems and Computer
Engineering, Carleton University
1125 Colonel By Dr.
Ottawa, ON K1S 5B6, CANADA

Youssef Bouanan
Gregory Zacharewicz
IMS Laboratory, UMR 5218
University of Bordeaux
351, Cours de la Libération
Talence, 33400, FRANCE

Adolfo López Paredes
[+]INSISOC, University of Valladolid,
C/ Paseo del Cauce 59.
E47011 Valladolid, SPAIN

ABSTRACT

Recent disasters have shown the need to improve emergency plans and the importance of the communications while managing the emergency. These communications can be modeled as an information transmission problem in multiplex social networks in which agents interact through multiple interaction channels (layers). Here, we propose a hybrid model combining Agent-Based Modeling (ABM), Discrete Event System Specification (DEVS), Network theory and Monte Carlo Simulation. We explore how the information spread from agents in an emergency plan taking into account several communication channels. We developed formal and simulation models of information dissemination in such emergency plans. We reuse a model architecture based on ABM, DEVS & Network Theory taking into account the behavior of the nodes in the network and the different transmission mechanisms in the layers. Finally, we execute a scenario to observe the communications using a DEVS network modeling platform powered by VLE.

1 INTRODUCTION

In contemporary societies, crisis and disasters are common. Some examples of natural disasters in recent history include the Earthquake in Chile in 2015, Hurricane Sandy in 2012, the Earthquake and Tsunami in Japan in 2011, and the Earthquake in Haiti in 2010. Likewise, the Darfield Earthquake in New Zealand in 2010, the Cyclone Nargis in Myanmar (Southeast Asia) in 2008, Hurricane Katrina in 2005, the Earthquake and Tsunami in Indian Ocean in 2004 and others show the numerous disasters with serious consequences. Besides these natural disasters, industrial disasters have also produced serious problems. Some examples include the Savar building collapse, the Rana Plaza collapse in Bangladesh in 2013, and the explosion at a Consolidated Edison Inc. power plant in New York City's East Side in 2012. Similarly, the accident at TEPCO's Fukushima Nuclear Power Plant (NPP) in 2011, the explosion of the power plant in Connecticut in 2010 or the Imperial Sugar refinery explosion in Georgia in 2008, etc. have caused serious human and financial tragedies. Sometimes, a natural disaster is the trigger for an industrial one. For example, the accident at TEPCO's Fukushima NPP follows the Earthquake and Tsunami in Japan in 2011, or the explosion at the Consolidated Edison Inc. power plant following Hurricane Sandy in 2012.

When a natural or industrial disaster occurs, the consequences can be devastating. There can be many deaths and injuries, and during the emergency, normally first responders need to take care of the evacuation of many agents. The disaster may also carry breakdowns in the infrastructure or failures in the energy systems. However, when both occur at the same time, the consequences are even worse. In these situations, making decisions about where to allocate the resources becomes more difficult. First responders have to decide which situations have priority and allocate the resources accordingly.

978-1-5090-4486-3/16/$31.00 ©2016 IEEE

Normally, after the disaster, various organizations analyze the consequences of the disaster. These studies normally include a study on how the crisis was managed, identifying the strong and weak points in the crisis management. This analysis is used subsequently for improvement in future emergencies. Because of these analyses, we now know that is very important to manage the communication systems during the emergencies. For example, after the accident at TEPCO's Fukushima NPP, there was a request to review the communication and management systems in the emergency plans (Omoto 2013). Likewise, the International Atomic Energy Agency (IAEA) suggested to strengthen the management systems, the response arrangements, the transparency, and the effectiveness of the communications mechanisms (Langlois 2013). In similar studies, Kendra and Wachtendorf examined the World Trade Centre attack in September 2001 (Kendra and Wachtendorf 2003), and they found that the design of the organization, the training and preparation were key elements to recover from the attack. However, also creative thinking, flexibility and the ability to improvise were found important factors to deal with the situation.

These reviews suggest that the communications and the internal structure of the organizations are key for managing the emergency. Hence, we want to provide new methods for studying these organizational structures, and for identifying if they are robust enough or not under different emergency scenarios.

The structure of the internal organization and the communications among its participants can be modeled as a problem of information transmission in multiplex networks (represented as directed graphs). The idea is to build such a network in which the nodes in the graph represent the individuals in the organization, and the links between them represent the communication relations. In order to show our proposed methodology, we used a case study based on an existing Nuclear Emergency Plan (NEP) from Spain.

Initially, we studied this problem by using network theory (Newman 2003) and implemented our case study using Gephi (Bastian et al. 2009). The goal was to build a model of a real NEP, and to do so we collected information from experts in the Spanish NEP. We identified the agents involved in the plan, its organizational structure, their communication mechanisms (distinguishing the different technologies used by the agents to communicate with each other), and the messages and actions that the agents take before (preventive), during (control and mitigation) and after (recovery) the emergency (Ruiz-Martin, Ramirez-Ferrero, et al. 2015). Our formal model, based on network theory, was used to study the characteristics and properties of the communication and the command chain network inside the NEP. In (Ruiz-Martin, Lopez-Paredes, et al. 2015), we also studied how a downfall in the different technologies affects the robustness of the communication structure. These analyses provided important results to understand how the emergency plan works and to propose improvements in terms of its communication structure.

However, using this methodological approach has some limitations. We needed to assume that all communication technologies are equivalent, and we needed to study our network as a simplex one. Although multiplex networks can include specific properties in each layer, characterizing the interconnections between layers and the appropriate global network description measures is still challenging (Gómez et al. 2013). Moreover, in order to study our network, we needed to consider it as a static model, not being able to change the scenario dynamically (we constructed the network for each scenario, and studied it as a simplex static one). This approach do not allows us to include dynamics on the network: we cannot include dynamic changes in the topology nor to include different behaviors of the nodes.

In order to solve these limitations, we propose a hybrid of methodologies and tools: Agent Based Modeling (ABM), Discrete Event System Specification (DEVS), and Network Theory to develop the model of the emergency plan. The main advantages of this methodology combination are as follows:

- It can simulate the information transmission in the network taking into account the different properties of the underlying technologies and different behaviors of the nodes.
- It is based on a formal modeling and simulation (M&S) methodology – DEVS. The use of DEVS allows us to separate the development of the model and its implementation easily.
- It can combine the simulation models with stochastic simulation in order to generate multiple simulation results at random, and we can use advanced analytic techniques (in our case, R and the RStudio toolkit) to improve the analysis of the results.

In the following sections, we will present an architecture based on ABM, DEVS and Network Theory to simulate the information transmission in emergency plans taking into account the behavior of the nodes in the network and the different transmission mechanisms in the layers.

To achieve this goal, we will first explain the case study we will use: a real NEP from Spain. Then, we will show how we can generate the network and the whole topology based on the case study. We will also show how we can easily run different scenarios using RStudio: we can add and delete communications links easily, we can simulate if some agents come to help in the emergency or some agents goes out. We will also show the visualization of the results provided by RStudio. The main objective of the paper is not to study the behavior of the individual in the emergency plan or the specific properties of each communication technology, but to present a new architecture to do this type of analysis.

2 RELATED WORK

In recent years, we have seen different research dealing with emergency management. For example, there are new methods for evacuation (Lv et al. 2013; Hammond and Bier 2015), studies about the relation between task complexity and its development time (Park and Jung 2007), and new training and decision support tools for emergency management (Bañuls et al. 2013; Karagiannis et al. 2010; Mendonça et al. 2006). Other examples include works like (Kanno et al. 2008), in which the authors presented a simulator for analyzing coordination and communication taking into account the behavior of the individuals. Such simulators are based on informal M&S methodologies and testing and validation is complex.

A simulation study consists of several phases, for example, phenomenon identification, conceptual modeling, input and output data analysis, model translation/implementation, verification, validation and experimentation. In Mustafee et al., authors distinguish between hybrid simulation and hybrid M&S study based on the techniques applied, and also the stage in which they are applied (Mustafee et al. 2015). According to (Powell and Mustafee 2014), on the one hand, the use of multiple M&S techniques in the model implementation stage is referred to hybrid simulation. On the other hand, hybrid M&S study refers to the application of methods and techniques from different disciplines such as operations research (other than M&S), systems engineering and computer science to one or more stages of a simulation study.

Here, we present an hybrid architecture based on ABM, DEVS and Network Theory to simulate and study the information transmission in emergency plans taking into account the behavior of the agents (nodes in the network) and the different mechanisms in the layers. Our work differs from existing simulators because it is based on a formal M&S methodology. The use of DEVS (Zeigler et al. 2000) allows us to separate the development of the model and its implementation easily. Moreover, it modularity allows us to easily adapt the model to study the communications in other emergency plans or to easily adapt the behavior when more information are provided by the experts. It also provides a formal model to be tested and validated. The use of Network Theory (Newman 2003) and ABM (Bonabeau 2002) also give us a framework to develop the model based on the information provided by the experts.

Discrete Event system Specification (DEVS) (Zeigler et al. 2000) is a formalism for modeling Discrete Events Systems. The hierarchical and modular structure of DEVS allows defining multiple models that are coupled to work together in a single and model by connecting their input and output through messages (Wainer, 2009). In the same way, the resulting model can also be coupled with others models defining multiple layers in the hierarchical structure. In DEVS, atomic models define the behavior of the system, and coupled models describe the structure of the system. VLE (Virtual Laboratory Environment) software (Quesnel et al. 2009) implements DEVS M&S and supports multi-modeling, simulation and analysis. In (Bouanan et al. 2016), the authors used VLE to instantiate a DEVS model from the description of a social network (represented by individual attributes and relationships). This simulation is used to study the dynamicity of the network (i.e. propagation of information).

Agent based modeling (ABM) has recently been used for a variety of applications (Macal and North 2010). ABM offers various types of agents, models of their behavior and characteristics, through a range of architectures and components libraries. Agent-based social simulation (ABSS) consists of social simulations that are based on agent-based modeling and are implemented using artificial agent technologies (Davidsson 2002). Different agent-based platforms have been used for implementing agent-based social simulation (Tobias and Hofmann 2004). Most of the simulation frameworks are oriented towards applications in the field of artificial intelligence; thus we developed a new library for DEVS Networks (Bouanan et al. 2016) based on VLE toolkit in which agents can be modeled as free and complex objects.

Network theory (Newman 2003) allows studying graphs (networks) that represent relations between discrete objects. A network is defined as set of nodes connected by links. For example, nodes can represent cities, agents, train stations, computers, airports, etc. If the nodes are airports, the links can for example represent commercial routes, tourist routes, ground transportation, etc. There are various metrics to characterize and extract properties from a network: the density, diameter, degree distribution, clustering, modularity, number of connected components etc. In (Ruiz-Martin, Ramirez-Ferrero, et al. 2015) we explain how these metrics are understood while analyzing the communication in emergency plans.

As discussed earlier, we want to study the dissemination of information in emergency plans through simulation in order to identify the key characteristics that have the greatest influence on the emergency management. Identifying these characteristics, we can define emergency plans that are more robust. In our approach, we use the R programming language to drive our simulation and analyze the results in order to understand the influence of different parameters in the information transmission process (communications means available, behavior of the agents, individuals available, etc.). R is a language and environment for statistical computing and graphics (Ihaka and Gentleman 1996) that provides statistical and graphical methods (linear and nonlinear modeling, time-series analysis, classification, clustering, etc.). RStudio (Team 2014) is an open-source integrated development environment (IDE) for R.

3 A HYBRID ARCHITECTURE FOR MODELING EMERGENCY PLANS

Formal methods, models and tools for social data are largely limited to graph theoretical approaches informed by conceptual developments in social network analysis. (Bouanan et al. 2016) have provided an integrated modeling approach to social data across the conceptual, formal and software realms. It uses a conceptual model for social data, a formal model of such data based on expert information and network theory, and a schematic model of a simulation module informed by the conceptual and formal models as shown in Figure 1.

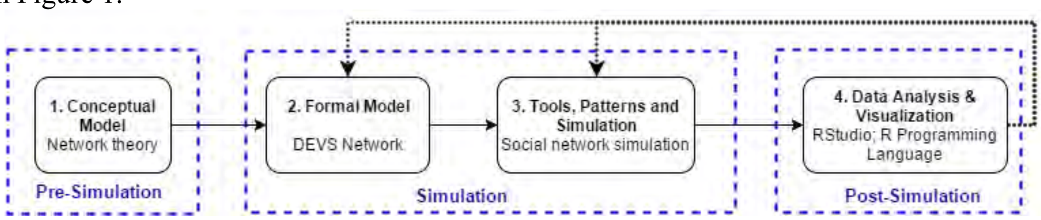


Figure 1: Hybrid architecture for modeling emergency plans.

The architecture in Figure 1 is a hybrid combination of methods for M&S of emergency plans:

- **Pre-simulation:** We define a new conceptual model consisting of a NEP organization using network theory. Such experiment includes one or several groups in the organization, each with many agents. Sometimes, a group of people is model as a single agent, and a network represents all relations between agents. We store the information in a database making each experiment accessible and re-playable. The repository contains all the individual static models.
- **Simulation:** The process starts with transforming the static models of the NEP organization to a *Formal Model:* a DEVS network is built automatically by instantiating an atomic DEVS model. Each NEP agent is specified as an atomic model, or, if it has a complex dynamics as a coupled model with micro behavioral and evolution rules. DEVS is used for defining each entity and simulating the behavior of the agents dynamically. This simulation is run using VLE (Box 3).

- **Post-simulation:** We use R to processes the results. The result files are used to visualize the simulation and to conduct analysis. The analysis can lead to a new cycle. This allows focusing on critical parameters (communication channels) that determine the model output (influenced agent).

The hybrid agent-based simulation uses a MySQL database for input, a DEVS-based simulation model and RStudio to analyze and visualize the output results. These tools are used to generate and analyze the process of information propagation in the network generated in the first step (Box 1 Figure 1). The simulation starts with the experiment to simulate. The *GraphLoader* connects to the database to retrieve all the network configuration information from the experiment. It transforms this dataset into a DEVS coupled model called *DEVS network*. Another DEVS atomic model, the *Generator*, is used to prepare the information item to be spread through the network. The simulation is driven by an R script to produce a result set, which we processed to conduct statistical analysis and to display results (Figure **2**).

This framework supports dynamic reconfiguration of the models based on the properties of the DSDEVS Formalism. Nevertheless this feature is not exploited in this paper (i.e. no add/suppress links and models at runtime). In the presented scenarios, links (layers) are de/activated at initialization (t0). The study focused on the use of this new hybrid architecture to analyze communications in emergency plan.

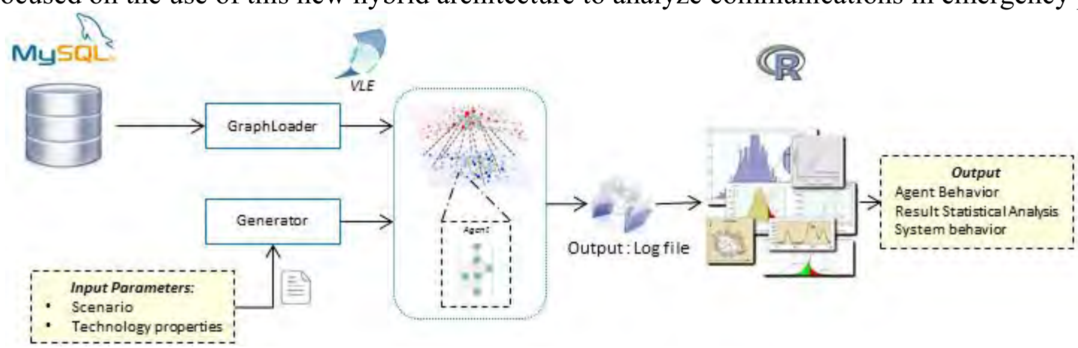


Figure 2: Hybrid agent modeling and simulation for Emergency Plan.

Thinking about the relationships between people as a network, and seeing people inside the network as agents make it easier to design a conceptual model. In our model, we expect that information exchanged between people can arise at any time and on a great number of occurrences. DEVS answers to these needs; it provides a suitable framework to make a formal and executable model of the conceptual model developed using ABM and network theory.

The major problem in this approach is that network size (number of individual) is usually large, besides the study attends to consider and simulate different network connections. If there is many individual's behavior, it may be difficult to scale up the formal model. The modeler has to develop different DEVS models to include this variance. However, as DEVS models can be parameterized, we can significantly reduce the effort to customize after an appropriate design.

To solve the problem of simulating different configuration networks easily, the approach, proposed by (Bouanan et al. 2016), has been based on the *Model Driven Engineering* (MDE) approach to transform automatically a network configuration into DEVS network. It implements a *GraphLoader* tool that instantiates DS-DEVS models from networks (graphs) by using nodes and links properties. Then this abstract set of atomic models (mostly nodes) and coupled models (networks) are parameterized.

4 DEFINITION OF A NUCLEAR EMERGENCY PLAN

In order to show how to apply the architecture described in Section 3, here we present a case study based on a real external NEP from Spain. A comprehensive description of the case study can be found in (Ruiz-Martin, Ramirez-Ferrero, et al. 2015; Ruiz-Martin, Lopez-Paredes, et al. 2015). We will explain the most important characteristics related to the hybrid architecture proposed in this research.

The NEP follows the hierarchy in Figure 3. Several independent organisms are involved in managing the emergency, such as the radiological group (in charge of radiological control of the population and the first responders), the health group (in charge of their well-being and health), the logistical support group (in charge of providing support for food, evacuation, and coordination), etc. Each group has its own structure and sometimes their own communication mechanisms.

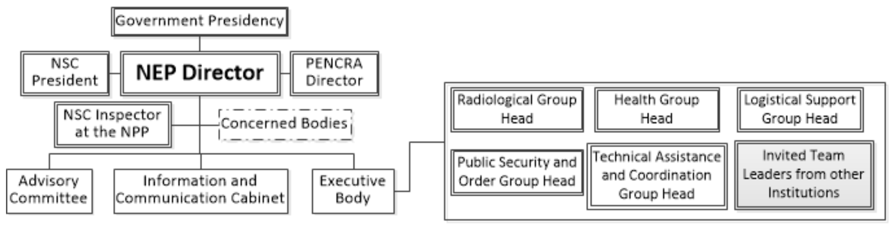


Figure 3: Sketch of the structure of the NEP (Ruiz-Martin et al., 2015a).

The communication mechanisms considered for the NEP include wired and mobile phones, fax, special mixed radio-phone, satellite, Internet, two different radio channels (Remer & Reman), and in-situ communication. Sometimes, members of the health group use beepers. Further, military communication channels can be used upon request, but they are not available until the infrastructure is deployed. We assume that the military channels are only used when other communication systems fails (i.e., we do not consider them as a basic communication channel used with the NEP organization).

The relations between the individuals in the organization are characterized by the organizational structure and the communication mechanisms used between them. In our previous works, we distinguished the communication technologies used by the agents but assumed that all the communication links were equivalent. This was a restriction of Network Theory and Gephi. Therefore, we ended up analyzing this multiplex network as a simplex one. We could not include different properties and different transmission mechanism between the different layers. With our proposed approach, these assumptions are not needed any further, and we can implement different transmission mechanisms for each layer.

Likewise, it is important to consider that the NEP communication structure is dynamic. The potential communications between individuals change with their location. Our previous research assumed a static topology, and we analyzed it using different scenarios. Here, we can simulate the dynamic network adding the location property to the nodes in a specific layer for agents in the same location at runtime.

While managing the emergency, there are two types of communications between individuals: those defined in the plan, and others based on social interactions (friendship, family, etc.). To explain the proposed architecture, we only take into account the communications defined in the plan. However, we can add social interactions by adding more communication layers and modifying the behavior of the agents.

We will show how to build a model of the plan based on our architecture, following Figure 3. We will only discuss the two first levels in the model, and a more detailed version for the radiological group, as the objective is only to show how to deal with these different levels of abstraction.

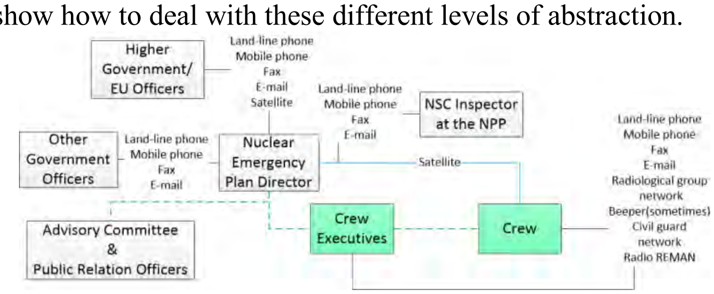


Figure 4: Higher abstraction level of the NEP model.

Figure 4 depicts the top level of the NEP structure. If we represent this model as a network, we have 7 nodes and 10 layers. This network will be translated into DEVS: each box in Figure 4 repents an agent (using ABM) which is translated into one server node model and several proxy models in DEVS.

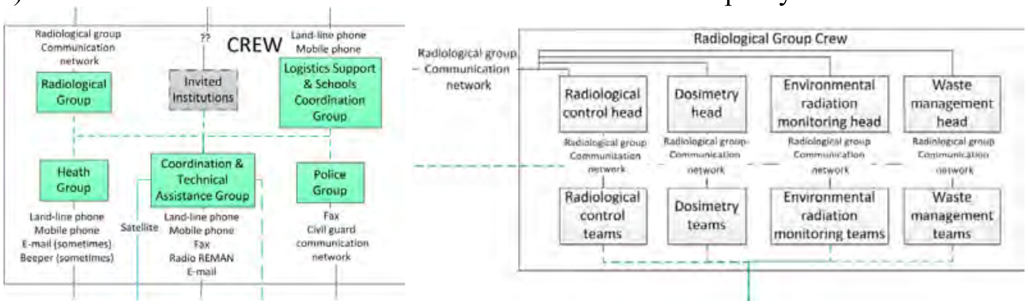


Figure 5: Second and Third level of abstraction: (a) crew and (b) radiological group crew.

The crew executives and the crew can be defined as in Figure 5 (a). In these models, each executive agent represents one person. For the crew, we decompose the radiological group in a third level of detail shown in Figure 5 (b). This hierarchical decomposition allows us to focus our interest in the level of detail we need depending on what we are analyzing. For example, if we are interested in studying how the radiological group works, we need the third level and maybe decomposing the teams in Figure 5 (b) further.

5 NEP MODEL DEFINITION AND SIMULATION

We first need to define the DEVS models according to specifications described in the previous section. To implement the agent models of Figure 2, we consider the information exchanged between agents through discrete-event messages whose values match the exchanges between the NEP individuals. The information reception is specified by input messages on the model's ports. The behavior of the model is driven by the DEVS transition functions. The combination of all the transition functions of the component models defines the autonomous behavior of the agent.

We used a number of DEVS models defined in (Bouanan et al. 2016), which were built using basic classes provided by VLE. To define the above agents and define the architecture presented in Section 3, we used two types of DEVS atomic models: *Server* nodes and *Proxy* models (describing filtering rules) in VLE. Each *Server* node is connected to several input and output *Proxy* models to describe the multi-layer agents. The proxy models represent how the information is transmitted in the network taking into account the different layer properties. When the input proxy receives information, it resends it to the server nodes. The output proxy model resends the information to all its input proxy model connections. The *Server* node models define the behavior of the agents and their reaction when they receive information.

The following example show a basic behavior: the agent receives information and it resends it to all its neighbors in all layers simultaneously. We assume that all nodes have the same behavior, as the main objective here is to show the architecture and the implementation of its different components.

Figure 6 shows an example of multi-network with 3 layers (i.e., 3 different types of communication) and 4 nodes (agents). Server Nodes are represented simultaneously in the three layers. Intra-layer interactions (represented with solid lines) show the connection between agents based on the communication channels. Dashed lines represent the inter-layer interactions (agents in different networks). Component P_x, P'_x, and P''_x are Proxy agents and they contain specific network rules for each individual. Each component has a specific behavior depending on the type of the link connecting it to the neighbors. The components are connected to a Server S_x representing the individual state and containing the individual rules.

For instance, when information arrives to P_1 on the "mobile phone" layer, then:

- The component P_1 sends an event to Server S_1
- S_1 reads the event and transmits the information to its networks, P_1, P'_1 and P''_1.

- Components P_1, $P^{'}_1$ and $P^{''}_1$ read the event and depending on their state and rules, can diffuse the information to their neighbors. In this case, P_1 already has the information and sends it to P_2; likewise, $P^{'}_1$ sends an event to $P^{'}_2$.
- Components P_2 and $P^{'}_2$ send an event to P_3 and $P^{'}_3$ respectively, etc.

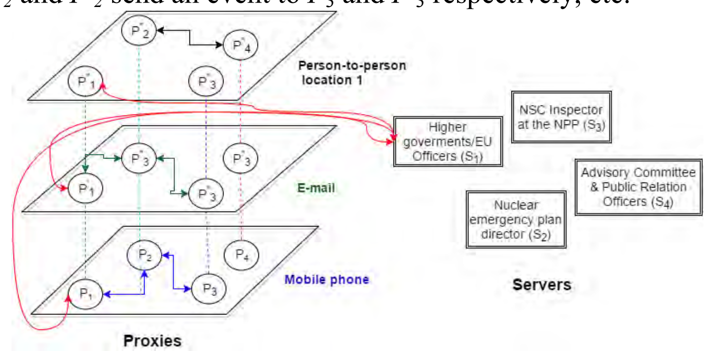


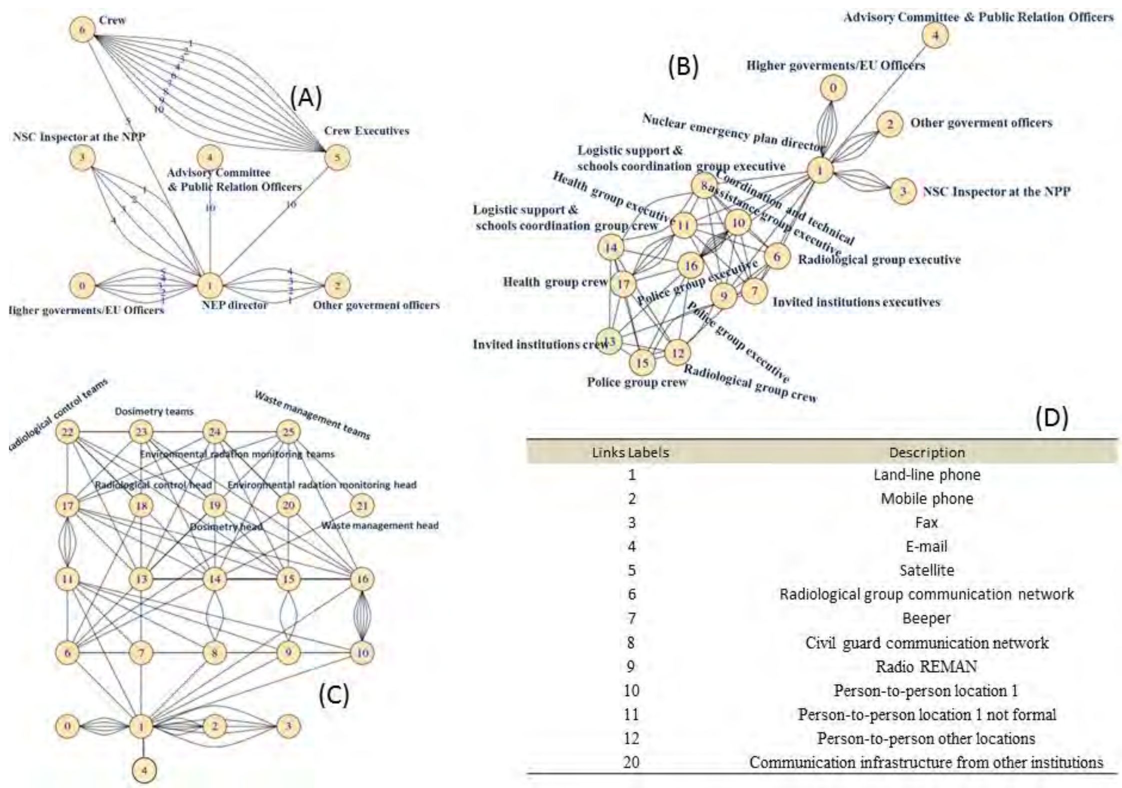
Figure 6: Sketch of the DEVS model architecture for a network with four nodes and three layers.

The model is constructed taking into account the connections defined in the network. We use *GraphLoader* (Bouanan et al. 2016) (an auxiliary model) to connect the proxy models to the server nodes taking into account the relations defined in the multiplex network This model inherits from the *devs::Executive* class, in order to be able to manipulate the connection graph. This is a Dynamic DEVS class (Barros 1997) that includes graph manipulation at runtime. We use other auxiliary models to generate the messages and the Event Logs, which are analyzed using RStudio. We use a *Generator* to generate messages to the starting points. A *Graphviewer* is connected to all server nodes. It allows observing the state of agent and sending it to a log file. We use an observation function based on events.

Following, we discuss the implementation of a case study for three different models for a Spanish NEP, representing different abstraction levels. Each DEVS network model (Figure 7) is built as explained above using the *Graphloader*. How we implement the behavior of the agents and how we set the information messages to be spread through is already explained above.

Each node in Figure 7 represents an agent, which is defined as a DEVS coupled model, as specified in Figure 6 (a *Server* node model and as many Input and Output *Proxy* models as communication layers in the model representing the communication mechanism in Figure 7d). The links in the figure represent the connections between DEVS coupled models. Figure 7a represents the highest level of abstraction, which considers all the Crew and Crew Executives as a single agent. It has 7 nodes (each node is a DEVS atomic model) and 10 communication layers. In Figure 7b, we decompose the Crew Executives and the Crew as specified in Figure 5. In this second level, we have 17 nodes and 12 communication layers. We show an example in further detail including one of the Group Crews (the Radiological). In this case, we obtained the network represented in Figure 7c with 24 nodes and 13 communication layers.

We have run three scenarios with the same group of people but with different configurations for the communication channels (Figure 7d). In each scenario, we generated the network based on the relationships defined in MySQL database and the micro behavioral model for each agent. In scenario 1, we simulate the information transmission process when the message starts in the director NEP (node 1) and the network includes all the agents without layers 11 and 12 (person-to-person communication may exist but it is not considered due to informal aspect and efforts to estimate agents' position). In scenario 2, we run 50 simulations by connecting the generator (at time 0) to the NEP director (node 1) and changing randomly the inactive layers (we deactivate two layers at random for each iteration). The goal is to show the impact of the communication channels on the management of emergency plans. In this case, we simulated the level three (the one with most details) and then we analyzed the results to verify the different hypotheses. Finally, in scenario 3, we deactivated layers 1, 2, 3, 4, 7, 11 & 12 to observe who cannot receive the message.



Links Labels	Description
1	Land-line phone
2	Mobile phone
3	Fax
4	E-mail
5	Satellite
6	Radiological group communication network
7	Beeper
8	Civil guard communication network
9	Radio REMAN
10	Person-to-person location 1
11	Person-to-person location 1 not formal
12	Person-to-person other locations
20	Communication infrastructure from other institutions

Figure 7: Graph representation of three different models of the NEP and description of link labels.

Figure 8 shows the simulation results of the three NEP models in Scenarios 1 (first row) and 3 (second row). The results show which agents can get the information based on the communication relations in the NEP, when the information starts in the NEP director (node 1).

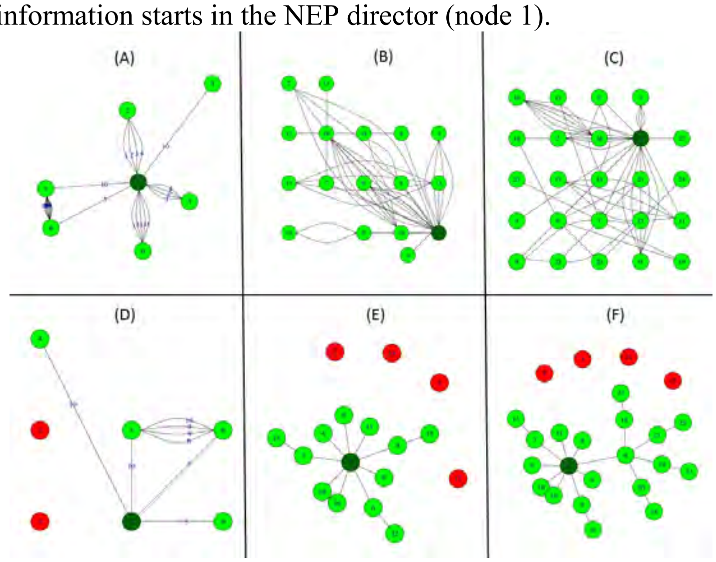


Figure 8: Simulation Results of information dissemination in NEP.

In the first scenario (i.e., all formal communications defined in the NEP are available, except those person-to-person communications based on the location), all the agents get the information. This is an expected result as everything is working as designed. In scenario 3, we represent a downfall in the Landline phone, Mobile phone, Fax, E-mail and Beeper communication mechanism. In this case, we see that some individuals do not get the information (represented in red color in the second row of Figure 8). These individuals differ in the different levels of abstraction of the model. However as we get a more detailed model, the number of isolated individuals increase. This is because in the higher levels of abstraction, we group individuals under the same agent and we consider that the communications in this high-level agent are supported by all the individual agents' communications. These results concur with the results obtained in our previous work (Ruiz-Martin, Lopez-Paredes, et al. 2015), where we got the same isolated individuals for this scenario.

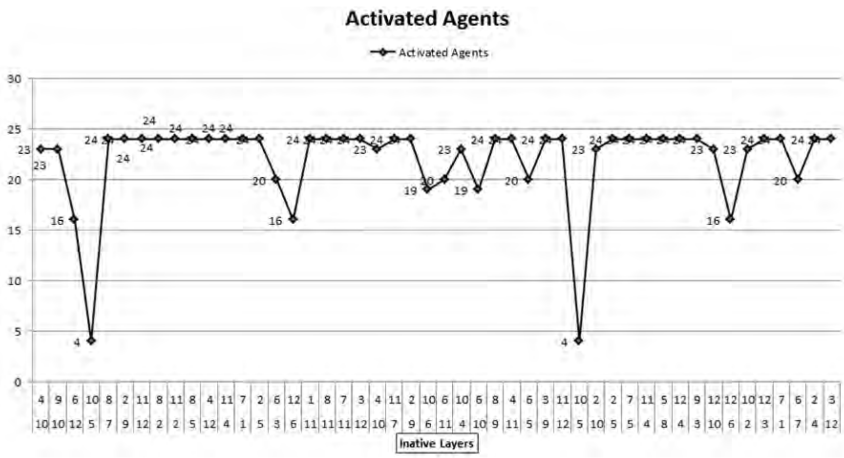


Figure 9: Number of active agent depending on communication channels.

Figure 9 shows simulation results for scenario 2 (random downfall in two communication layers at the same time) for the more detailed model of the NEP (Figure 7c). We represented the number of agents that receive the information. As we can see, there are redundant communication layers; for example, Beeper (7) and Landline phone (1). Other layers are critical; for example, if we do not allow person-to-person communications among the agents in location 1 and the Satellite fails, the information only gets to four nodes. With this last analysis, we can find the combination of downfall that result more critical in the information transmission process during the emergency.

6 CONCLUSIONS

We introduced an hybrid architecture of a multidimensional social network for modeling relationships between agents. The framework is based on ABM, DEVS and Network Theory to simulate the information transmission in emergency plans, taking into account the behavior of the nodes in the network, the network configuration and the different transmission mechanisms. The simulation allows observing the impact of the network structure in the message diffusion process. In addition, we provide statistical computing and graphics to enhance the simulation results in order to analyze graphically the dynamics (of nodes) on this network.

The simulation of three scenarios show how to identify key layers, which can affect the reception of messages by the people involved in the Emergency operation. We have shown how failures in the network topology and properties affect the information transmission. With a more accurate realistic behavior model of the agents and communications, we can make important conclusions about how these failures affect the emergency management. The use of the Proxy/Server architecture allows one easily adding or deleting a dimension in respect of the population's features.

We can use the architecture to study the dynamics of information transmission in multiplex networks taking into account that the propagation rules in different layers are different. This opens many possibilities for various application domains. Generating a population with an unseen level of cultural features can be used in marketing to simulate the adoption of a new product, in social science to observe dynamically the diffusion of information or the way an opinion changes and in management to study the impact of informal communication inside an organization.

ACKNOWLEDGMENTS

This work is partially supported by the SICOMORES Project (French DGA), University of Valladolid, Banco Santander and NSERC.

REFERENCES

Bañuls, V.A., Turoff, M. and Hiltz, S.R., 2013. "Collaborative scenario modeling in emergency management through cross-impact". *Technological Forecasting and Social Change*, 80(9), pp.1756–1774.

Barros, F.J., 1997. "Modeling formalisms for dynamic structure systems". *ACM Transactions on Modeling and Computer Simulation*, 7(4), pp.501–515.

Bastian, M., Heymann, S. and Jacomy, M., 2009. "Gephi: an open source software for exploring and manipulating networks". *ICWSM*, 8, pp.361–362.

Bonabeau, E., 2002. "Agent-based modeling: methods and techniques for simulating human systems". *Proceedings of the National Academy of Sciences*, 99(suppl. 3), pp.7280–7287.

Bouanan, Y. et al., 2016. "DEVS based network: modeling and simulation of propagation processes in a multi-layers network". In *Proceedings of the Symposium on Theory of Modeling & Simulation: Modeling and Simulation of Complexity in Intelligent, Adaptive and Autonomous Systems*. Pasadena, CA, USA.

Davidsson, P., 2002. "Agent based social simulation: a computer science view". *Journal of Artificial Societies and Social Simulation*, 5(1).

Gómez, S. et al., 2013. "Diffusion dynamics on multiplex networks". *Physical Review Letters*, 110(028701), p.5.

Hammond, G.D. and Bier, V.M., 2015. "Alternative evacuation strategies for nuclear power accidents". *Reliability Engineering and System Safety*, 135, pp.9–14.

Ihaka, R. and Gentleman, R., 1996. "R: a language for data analysis and graphics". *Journal of Computational and Graphical Statistics*, 5(3), pp.299–314.

Kanno, T., Makita, J. and Furuta, K., 2008. "Simulation of multi-organisational coordination in emergency response for system resiliency". *International Journal of Technology, Policy and Management*, 8(4), pp.442–459.

Karagiannis, G.M., Piatyszek, E. and Flaus, J.M., 2010. "Industrial emergency planning modeling: a first step toward a robustness analysis tool". *Journal of Hazardous Materials*, 181(1-3), pp.324–34.

Kendra, J.M. and Wachtendorf, T., 2003. "Elements of resilience after the World Trade Center disaster: reconstituting New York City's Emergency Operations Centre". *Disasters*, 27(1), pp.37–53.

Langlois, L., 2013. IAEA "Action plan on nuclear safety". *Energy Strategy Reviews*, 1(4), pp.302–306.

Lv, Y. et al., 2013. "A scenario-based modeling approach for emergency evacuation management and risk analysis under multiple uncertainties". *Journal of Hazardous Materials*, 246-247, pp.234–244.

Macal, C.M. and North, M.J., 2010. "Tutorial on agent-based modelling and simulation". *Journal of Simulation*, 4(3), pp.151–162.

Mendonça, D. et al., 2006. "Designing gaming simulations for the assessment of group decision support systems in emergency response". *Safety Science*, 44(6), pp.523–535.

Mustafee, N. et al., 2015. "Investigating execution strategies for hybrid models developed using multiple M&S methodologies". In *Proceedings of the 48th Annual Simulation Symposium*. pp. 78–85.

Newman, M.E.J., 2003. "The structure and function of complex networks". *SIAM Review*.

Omoto, A., 2013. "The accident at TEPCO's Fukushima-Daiichi nuclear power station: what went wrong and what lessons are universal?". *Nuclear Instruments and Methods in Physics Research Section A:*

Accelerators, Spectrometers, Detectors and Associated Equipment, 731, pp.3–7.
Park, J. and Jung, W., 2007. "A study on the development of a task complexity measure for emergency operating procedures of nuclear power plants". *Reliability Engineering & System Safety*, 92(8), pp.1102–1116.
Powell, J. and Mustafee, N., 2014. "Soft or approaches in problem formulation stage of a hybrid M&S study". In *Proceedings of the 2014 Winter Simulation Conference*. A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds. pp. 1664–1675. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
Quesnel, G., Duboz, R. and Ramat, É., 2009. "The Virtual Laboratory Environment: an operational framework for multi-modelling, simulation and analysis of complex dynamical systems". *Simulation Modelling Practice and Theory*, 17(4), pp.641–653.
Ruiz-Martin, C., Ramirez-Ferrero, M., et al., 2015. "Modelling of a nuclear emergency plan: communication management". *Human and Ecological Risk Assessment: An International Journal*, 21(5), pp.1152–1168.
Ruiz-Martin, C., Lopez-Paredes, A. and Wainer, G.A., 2015. "Applying complex network theory to the assessment of organizational resilience". *IFAC-PapersOnLine*, 48(3), pp.1224–1229.
Team, Rs., 2014. "RStudio: integrated development for R". *RStudio, Inc., Boston, MA. URL http://www. RStudio. com/ide*.
Tobias, R. and Hofmann, C., 2004. "Evaluation of free Java-libraries for social-scientific agent based simulation". *Journal of Artificial Societies and Social Simulation*, 7(1).
Zeigler, B.P., Praehofer, H. and Kim, T.G., 2000. *Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems*, Academic press.

AUTHOR BIOGRAPHIES

CRISTINA RUIZ MARTIN is a Ph.D. student in Industrial Engineering (University of Valladolid, UVa) and Systems and Computer Engineering (Carleton University). She received an Engineering degree, a M.Sc. and a Master in Project Management from UVa. Her email address is cruiz@eii.uva.es

YOUSSEF BOUANAN is a Ph.D. Candidate in ECE at University of Bordeaux. He received his Engineer degree from School of Engineering Science, Morocco and a M.Sc. in Enterprise System Engineering from University of Bordeaux, France. His email address is youssef.bouanan@ims-bordeaux.fr.

GABRIEL A. WAINER is Professor at the Department of Systems and Computer Engineering at Carleton University. He is a Fellow of the Society for Modeling and Simulation International (SCS). His email address is gwainer@sce.carleton.ca.

GREGORY ZACHAREWICZ is Associate Professor HDR at University of Bordeaux and IMS Lab with both competences in enterprise engineering and computer sciences. His email address is gregory.zacharewicz@ims-bordeaux.fr.

ADOLFO LOPEZ PAREDES is Professor at UVa. His research within INSISOC includes project management, simulation of social and economic behavior and industrial policy. He is Fellow of the European Academy of Industrial Management, and Director of INSISOC. His email address is aparedes@eii.uva.es.