A HYBRID SIMULATION METHODOLOGY TO EVALUATE NETWORK CENTRIC DECISION MAKING UNDER EXTREME EVENTS

by

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ABSTRACT

Currently the “network centric operation” and “network centric warfare” have generated a new area of research focused on determining how hierarchical organizations composed by human beings and machines make decisions over collaborative environments.

One of the most stressful scenarios for these kinds of organizations is the so-called “extreme events.” This dissertation provides a hybrid simulation methodology based on classical simulation paradigms combined with social network analysis for evaluating and improving the organizational structures and procedures, mainly the incident command systems and plans for facing those extreme events.

According to this, we provide a methodology for generating hypotheses and afterwards testing organizational procedures either in real training systems or simulation models with validated data.

As long as the organization changes their dyadic relationships dynamically over time, we propose to capture the longitudinal digraph in time and analyze it by means of its adjacency matrix. Thus, by using an object oriented approach, three domains are proposed for better understanding the performance and the surrounding environment of an emergency management organization.

System dynamics is used for modeling the critical infrastructure linked to the warning alerts of a given organization at federal, state and local levels. Discrete simulations based on the defined concept of “community of state” enables us to control the complete model. Discrete event simulation allows us to create entities that represent the data and resource flows within the organization.

We propose that cognitive models might well be suited in our methodology. For instance, we show how the team performance decays in time, according to the Yerkes-Dodson curve, affecting the measures of performance of the whole organizational system. Accordingly we suggest that the hybrid model could be applied to other types of organizations, such as military peacekeeping operations and joint task forces. Along with providing insight about organizations, the methodology supports the analysis of the "after action review" (AAR), based on collection of data obtained from the command and control systems or the so-called training scenarios.

Furthermore, a rich set of mathematical measures arises from the hybrid models such as triad census, dyad census, eigenvalues, utilization, feedback loops, etc., which provides a strong foundation for studying an emergency management organization.

Future research will be necessary for analyzing real data and validating the proposed methodology.

When I was six years old, I observed pictures from Biafra, where starving children were trying to survive. After forty years, I continue to observe the same problems in Darfur, Sudan. This dissertation is dedicated to all children in the world who do not have the same opportunities that God, my dear parents Sergio and Maria Angelica and my country provided for me. I hope to do something significant for those children.

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LIST OF ACRONYMS/ABBREVIATIONS

AAR	After Action Review
ABM	Agent Based Modeling
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
DEA	Data Envelopment Analysis
DES	Discrete Event Simulation
DDM	Distributed Decision Making
DoD	US Department of Defense
DMU	Decision Making Units
DOE	Design of Experiment
EOP	Emergency Operation Plan
ICS	Incident Command System
LP	Linear Programming
NCDM	Network Centric Decision Making
NEC	Network Enabled Capacity
NCW	Network Centric Warfare
NGO	Non Governmental Organization
NIMS	National Incident Management System
OO	Object Oriented
SD	System Dynamics

SNA	Social Network Analysis
TADMUD	Tactical Decision Making Under Stress
UML	Unified Modeling Language

CHAPTER ONE: INTRODUCTION

Background of study

In order to model a system, people involved in simulation have a tendency to use the traditional techniques based upon either discrete or continuum approach. Practitioners rarely combine two or more techniques for representing their models. On the other hand, simulations have been used extensively for modeling physical systems, and those do not adequately include methods for studying people making decisions in a collaborative environment.

Simulations for representing decision making structures have been limited to the use of cognitive frameworks, and only a few models have been published based on either discrete simulations or agent-based modeling. In general, organizational simulations based on quantitative techniques are either scarce or poorly documented.

At present, the network centric concept has enabled a new approach to mathematical analysis regarding how civilian and military organizations perform over a linked environment. In the previous context, the current challenge with modeling and simulating is dealing the scenarios in which the organizations have to make decisions under pressure due to extreme events (such as tsunamis, forest fires, urban chaos, chemical accidents, peacekeeping missions), since these problems take place either in the infrastructure supporting the network-centric process or in information, coordination, resource management, and synchronization of tasks.

We suggest that a hybrid simulation implementation could be useful for modeling a network centric decision making environment. The collection of data obtained in this model would allow the identification of bottle necks, procedure validation, quantification of reaction time, job loading, and new layouts, among other characteristics.

This research proposes a hybrid simulation based exclusively on mathematical and simulation foundations, and it will not incorporate any cognitive framework. The goal is to create a framework to acquire knowledge about the organizational structure in different stages of crisis situations through metrics and measurements of merit.

Problem statement

In the past decades three simulation approaches have been used widely for representing discrete processes, aggregated levels, and agent-based behavior. However, this will likely change in the future, as complex organizational systems really require elements of all three approaches in order for their complexity to be appropriately captured (Dooley, 2002).

We support the idea that the simulation community needs to combine simulation techniques that can represent the dynamic behavior produced in an *organization in the loop*. Mapping real entities into a simulated environment requires use of the three main simulation paradigms.

Current simulation systems such as constructive simulation do not fit very well for analyzing organizational behavior, because in these systems the outcomes are produced by the models, and we need to collect data from the real human behavior and not that performed by synthetic models.

However, when researchers have to analyze real organizations (such as organizations in the loop or C2 systems), the main problem is how to collect data for modeling, validating, and evaluating those structures, especially when there are many decision making nodes and a great deal of information being sent between them. For instance, if we analyze an organization with 100 nodes (each node is composed of one or more persons) we could collect as many as 9,900 types of pairwise interactions.

The current network centric environment enables us to collect data from systems based on information technology; therefore, the procedures made for hierarchical organizations could be captured and modeled. Lin (1994) stated that simulation provides insight for the evaluation of organizational designs with less cost than conducting human experiments, and once the main factors have been identified, human experiments can be done to test the theoretical results. We argue that the difficulties for simulating distributed decision making is still complex and likely never will be validated, but in the context of emergencies and disasters, the use of clear and well documented incident command system (ICS) and the data collection from the C2 systems should allow us to explore the design of synthetic models of contingency that enable the decision makers to know what happened, how it happened, and how could improvements be made in the future.

This dissertation defines an emergency organizational structure as a "complex system which performs as a network," and according to Dooley (2002) such a system should be modeled with a hybrid approach that incorporates the three main simulation techniques. Furthermore, we identify the need to combine simulations of organizational networks with a topological analysis of their structures and the identification of statistical properties which emerge from their behavior.

Scope of research and hypothesis

A hybrid simulation based on the three main simulation paradigms – System dynamics (SD), Discrete event simulation (DES), and Agent based modeling (ABM) – will be the basis of our methodology for modeling the network centric decision making environment performed by an organization facing extreme events. The theory of social network analysis (SNA) will allow analysis of the dynamic changes produced in organization structures over time. The collection of data obtained from the models will allow the identification of metrics and measures of merits such as bottle neck, identification, procedure validation, reaction time measurement, job loading identification, dangerous event identification, automatic modification of security policy, and "just-in-time" modification of organizational procedures, among other characteristics. Furthermore, mapping real flows and critical tasks into a simulated environment will enable the detection of possible vulnerabilities.

The simulation methodology should cooperate with the decision makers in three scenarios:

- To assess the behavior of different nodes (in the after action review analyzed messages flows and resources flows).
- To design better organization structures making use of micro-world scenarios.
- To control the performance of different roles in real time (*organization in the loop*).

Figure 1 shows a network centric environment in which an emergency organizational structure depicts dynamic behavior over time. The network centric environment is a system of systems with an initial layout, nodes, and endogenous variables; therefore relationships of causality can be identified, modeled, and simulated. The exogenous variables strike the system over a specific location, and they produce an immediate reaction of one node, a subset of nodes or of the whole system. Notice this approach presents multiple opportunities for analyzing organizational layout, information flows, resources flows, and tasks synchronization.

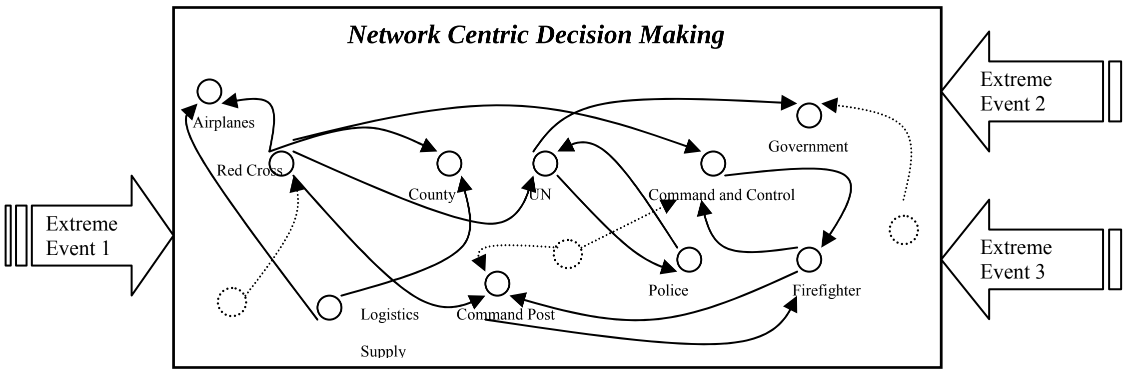


Figure 1: Representation of a hybrid simulation

The hybrid simulation combines the network's analysis with the procedural behavior and interactions shown by the nodes. Thus this dissertation proposes the following sets of hypotheses.

Hypothesis 1: With the purpose of detecting metrics and vulnerabilities, a hybrid simulation based on DES, SD and ABM is an adequate platform to represent the dynamic sequences produced in an "organization structure" when it faces different extreme events.

Hypothesis 2: A hybrid simulation can be combined with social networks analysis and linear programming in order to assess the evolution of an organization structure over time, and this type of simulation is suitable for detecting bottle necks, quantification of reaction time, loading job, vulnerabilities, priorities, and synchronization, among other measures of performance.

Contributions

There are three main schools of simulation practice; DES, SD, and ABM. Simulation researchers typically remain in one camp and do not work in all three domains. Characteristics of each of the three simulation approaches are shown in Table 1 (Dooley, 2002).

Table 1: Three main paradigms in simulation (Dooley, 2002)

Simulation approach	Condition for use	Main characteristics
Discrete event	System described by variables and events that trigger change in those variables.	Events that trigger other events sequentially and probabilistically.
System dynamics	System described by variables that cause change in each other over time.	Key system variables and their interactions with one another are explicitly (mathematically) defined as differential equations.
Agent-based	System described by agents that react to one another and the environment.	Agents with schema that interact with one another and learn.

This research presents a hybrid methodology, since it puts together the three main simulation paradigms for modeling organizational structures facing extreme events. As the organization changes dynamically over time, the different states of the organization will be analyzed according to the social network theory (based upon graphs) and eventually linear programming. Metrics and causal analysis will be obtained from the proposed hybrid model.

Therefore, these are the three main contributions identified in this research:

- To propose a methodology to understand the relationships in complex systems such as ICS for emergency response based upon the combination of social network techniques and simulation techniques.
- To propose a hybrid simulation scenario, based on DES, SD, and ABM, creating the conditions (if data is available) for modeling organizational emergency structures which develop their tasks over a network centric environment. Furthermore, the hybrid simulation could be applied to another type of organization, such as military peacekeeping operations and joint task forces.
- To provide a framework for study of the lessons learned concept in military and civilian organizations and to support the after action review (AAR), base on the collection of data obtained from the C2 systems that an organization has in the network centric environment.

Dissertation outline

Chapter One presents the problem statement, scopes and hypotheses of this research. The main contributions also are named at the final part of the chapter.

Chapter Two describes the literature review emphasizing in the terms of network centric warfare and network centric decision making. The concept of *extreme event* and its implications for a distributed decision-making process are defined. The literature review includes the previous intent for modeling and simulating organizations. The previous studies on social network analysis are explained in this chapter. A comprehensive review of the three main simulation techniques are described and contrasted in a table that shows which one is best situated for modeling and simulating selected problems.

Chapter Three presents the methodology and five semantic analyses of past extreme events.

Chapter Four describes the domains in which an emergency organization performs its tasks and defines the properties of a digraph from an incident command system perspective and additional techniques are discussed.

Chapter Five explains how to combine different simulation techniques, and also defines the conceptual hybrid model for analyzing organizational emergency structures.

Chapter Six proposes the implementation of a hybrid model, keeping parallel with the configuration of the command incident system represented as a digraph.

Chapter Seven presents the conclusions and proposes future studies for continuing this hybrid implementation.

CHAPTER TWO: LITERATURE REVIEW

Network centric warfare (NCW) and network centric decision making (NCDM)

There are similar characteristics in the way military and civilian organizations make decisions under extreme events; as a result, it is possible to identify models and methodologies which are useful in both types of organizations. Thus, the Army's network-centric approach to operations could serve emergency responders equally effectively (Committee on Army and Technology for Homeland Defense, C4ISR, 2004).

The NCDM takes its foundation from the NCW and network enabled capacity (NEC) concepts, the former from a US military perspective and the latter from a UK military perspective. NCW is the product of network connectivity, and the military uses this concept for increasing both strategic and tactical advantage in battle (MacMillan, Diedrich, Entin & Serfaty, 2005). NCW essentially encompasses the idea of interconnecting a heterogeneous range of actors and objects in the battle-space through telecommunication and computer networks (Bakken, 2004).

A fundamental assumption in NCW is that improving information infrastructures will improve military decision making and therefore military effectiveness (Hanzel & Fewell, 2004). Those characteristics could be useful for modeling and optimizing an emergency organization structure. One advantage is the gain which can be achieved by simply sharing information among the nodes. As Moffat notes,

> If the nodes are distributed globally, and each having a 5 percent probability of possessing a given piece of information that is needed to make a plan successful and the planner only has access to organic information, he would only have a 5 percent chance of

generating a successful plan. If the planner has access to *n* sources, he would increase the probability of having the information necessary to develop a successful plan to [$1 - 0.95^n$]…" (Moffat, 2003).

Even though that NCW theory proposes to achieve a tactical advantage by using information superiority and a well situated situation awareness shared by the whole organization, currently there are no systematic studies evaluating network-centric strategies versus alternative strategies (Finder, Fendley, Narayanan & Raymond, 2003). The author suggests that this research could be an initial test-bed for evaluating the alternative strategies mentioned by Finder et al.

Studies have been made to identify the benefits of NCW, but few have taken an analytical view and produced quantitative results. A study was conducted by five allied countries to redress the lack of quantitative evidence about network-centric capability. Using queuing theory models, the concepts of shared situational awareness and collaborative information environment were analyzed for improving anti-submarine warfare (Klingbeil & Galdorisi, 2004).

In a NCW environment there are intensive information flows between sensors, C2, shooters on a network of networks, and synchronization of information arrivals and updates. The elapsed time of each interacting component and the message delay can play a critical role in such scenarios. Estimation of delay is essential to verify if the system meets timing constraints. The message delays from each component system can change the order of task execution and may cause a synchronization problem.

In order to evaluate performance prediction of a NCW system, Shin and Levis (1999) implemented Petri net and queuing net for modeling functional and physical layers as shown in Figure 2. Their application modeled the information flow between sensors, C2, and shooters. An experimental system design was established based on two rules of engagement, seven input parameters, and four output parameters.

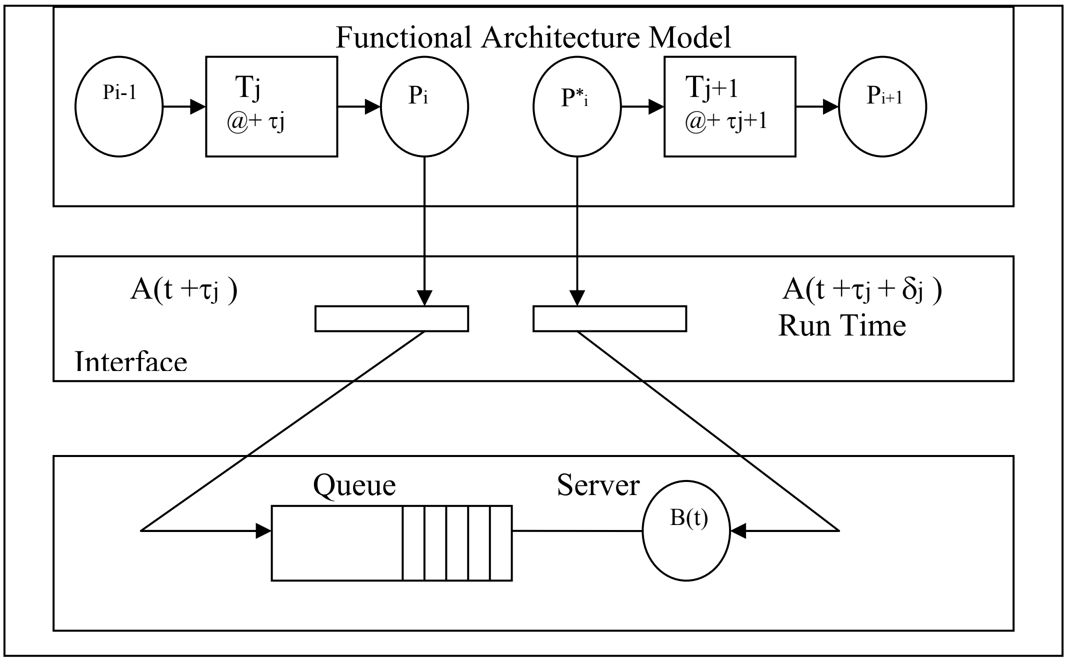


Figure 2: Functional and physical architecture models (Shin & Levis, 1999)

The above study supports the goal of this dissertation in terms of finding analytical models for simulating NCDM during emergency and crisis situations.

Most of the current studies about net-centric environments are focused on complexity theory, which is difficult to apply to real crisis situations; however there are a set of mathematical and statistical tools (such as queuing theory) which have been validated, and can support realistic organizational models for improving coordination and synchronization in emergency response organizations. The only premise for carrying out this goal is the requisite for collecting empirical data from real structures such as either a command and control system or organization in the loop (training system).

This research is intended for generalizing the network centric concept into a generic organization (civilian, military, or combined). Table 2 identifies similar features between NCW (military arena) and NCDM (organizational emergency environment).

Table 2: Contrast between NCW and NCDM

Features	Network Centric Warfare	Network Centric Decision Making
Sensors	Radar, units on the battlefields, UAV, airplane, etc.	Seismographs, early warning tsunami, people on the ground, etc.
Shooters	Weapons, troops on the ground, ships crew	Emergency responders for prevention or mitigation of the effects of extreme events
Decision Support and Analytic tools	Geographic information systems, expert systems, agents, data mining	Geographic information systems, expert systems, agents, data mining
Command, Control, Communication and Computers (C4)	According to the scenario and units: different levels. According to the force: coalition Interoperability.	According to the scenario and the event: different levels, but it is closer to C2 coalition interoperability
Intelligence, Surveillance, and Reconnaissance (ISR)	People, signals, sensors, photographe, satellite images, open sources information, UAV	People, photographes, satellite images, sensors
Situation Awareness	Common operational picture	Not well developed as of yet
Nodes	Military units, weapons systems, C4ISR, point of logistic support, sensors, hubs	Police, red cross, federal agencies, governor, mayor, C4ISR, NGO, fire rescue, sensors
Infrastructure	Military networks	Civilian networks, military networks
Grid	Communication grid Information grid	Communication grid Information grid
Scenarios	Battlefield (urban and ground)	Any place
Structure	Command chain	Depends on extreme events, fuzzy
Interoperability	Hard among coalition forces	Hard among different organizational nodes
Measures of Performances	In development.	Do not exist
Span of Control	Very well defined	Hard, fuzzy, depends on scenario, extreme event and time for reaction

Using the military approach, network-centric systems can be defined as those that make users more effective "by networking sensors, decision-makers and emergency responders to accurately see, understand and act on the situation facing them" (Committee on Army and Technology for Homeland Defense, C4ISR, 2004).

This dissertation has as its main assumption that an organizational structure prepared for facing extreme events works over a network centric system. Thus a model to represent a NCDM should encompass the following capabilities performed through real-time networking:

- All nodes of the network should have access to all networked resources according to their tasks and required knowledge for carrying out their missions (sharing of situational awareness).
- Networked decision makers can make more informed decisions.
- A networked organization can more effectively and efficiently synchronize its assets.

Distributed decision making

Distributed Decision Making (DDM) is a neologism which captures the cumulative change in the nature of multi-person decision making. This process is usually supported by technologies such as satellite communications, electronic messages, teleconferencing, and shared databases (Committee on Human Factors, 1990).

DDM is performed by either teams or organizations; usually researchers merge both concepts and do not give enough attention for defining each one separately. Blau and Scott (1962) defined a formal organization as a "purposive aggregation of individuals who exert concerted effort toward a common and explicitly recognized goal". On the other hand, Orasanu and Salas (1992) defined a team as a group whose members share a common goal and common task. Furthermore, Kang, Waised, and Wallace (1998) in their paper “Team Soar, a model for team decision making” argue that the most critical distinction between teams and groups is the degree of differentiation of roles or expertise relevant to the task and the degree of member interdependence.

Even though *team* and *organization* definitions present similar characteristics, general knowledge identifies the team concept as a small group of people who accomplish their task over a short timeframe and an organization as a long-lasting complex institution. This research will use the organization concept for studying network centric decision making under extreme events, since an organization presents procedures and hierarchies, which can be summarized as protocols or a set of rules, attributes essential for modeling and simulating an organizational structure.

The literature regarding “team decision making” suggests that teams make better decisions than individuals, especially for complex tasks (Prietula, Carley & Gasser, 1998). Nevertheless, the team performance will depend of the previous knowledge that it has of its tasks, the role and position of its members and the configuration that exists in the team.

Hazen and Fewell (2004) did research about the history of decision-making models, and they defined two branches that are not always clearly separated; the first one defines the aim of decision-making models to assist decision-makers in making better decisions (for instance Bayes’s theorem). The second identifies models which describe how decisions are actually made in practice and quantifies the quality of those decisions. This dissertation pursues the second approach, since the author is interested in simulating the way an organization performs under extreme events in order to collect the most significant parameters and enable quantitative analysis based on AAR and lessons learned methodology.

The organization structures for responding to extreme events usually accomplish their missions in separate locations. Depending on the type of event, there are many actors who support the decision making process. Those actors have different skills, knowledge, missions, and resources. In the previous context, one of the main challenges is trying to measure the performance of an organization both as a whole and as an individual role (The reader should note that an individual role can be configured by many people performing known tasks).

This dissertation proposes that the performance of those organizations should be measured when they face complex scenarios. These environments of tension can be characterized by four main features:

- The organization has clear procedures and structure for responding to the extreme events.
- There is a short time for decision making.
- Critical decisions must be made with vital results.
- There is collaborative work among all actors in the organizational structure.

Extreme event concept

Sarewitz and Pielke (2000) defined ten properties of extreme events and their associated implications for decision making. See Table 3.

Table 3: Properties of extreme events (Sarewitz & Pielke, 2000)

Properties	Implications for decision making
Rapid onset vs. "creeping change"	The decision making implication may be quite different for different events.
Rare	Little opportunity for learning. Relevant experience may be lacking. May or may not be a factor in evolutionary psychology. Rare events may control system evolution.
High consequence	Attention will be focused on event. Decisions matter.
High uncertainty	Generally, extreme events are difficult to predict. They often occur with insufficient warning. Some extreme events may be predicted months or years in advance (meteor strike, Y2K) but that may still not provide sufficient time or motivation for action.
Time pressure	Limited time for analysis. Stress producing.
Disruptive	Normal activities may cease. Loss of constancy. Stress producing
Pose complex, ill structured problem	This lack of structure may encourage intuitive mode of responding when analytic mode is more appropriate.
Potential to create long term change	In the aftermath of an extreme event, decision makers may face a new environment. Again, loss of constancy and stress are likely.
Affect large numbers of people and/or large ecosystems.	Group decision, leadership, government action, trust, and cooperation/communication among stakeholders are important for implementation of effective decisions.
Under-represented and disenfranchised groups tend to be disproportionately vulnerable.	Equity should be explicitly considered in decision making.

Generally speaking, the literature identifies extreme events with dangerous situations produced by man-made or natural disasters; we include the previous approach, but do not exclude those critical events which affect organizational structures, such as a problem in the banking system due to an unexpected stock market slump, a lack of raw materials in a factory due to an interruption in the supply chain, or the sudden failure of critical infrastructures such as an electrical blackout. This research is an attempt to identify and simulate similar pattern behavior in highly hierarchical organizations, with known procedures which must face critical and unusual situations.

Brunner (2000) described some extreme events as those which disrupt the routine practices of many people at the same time, such as the OPEC oil embargo in 1971 which produced long waiting lines at gas stations, among other consequences. Pielke (2000) described different models which represent the natural observable fact named extreme event, but he did not model the effect that these events could produce in an organization.

Mendonca and Wallace (2003) pointed out that extreme events are those which create the need for cooperation among responding organizations. Activities to mitigate the effects of these events can be expected to range from planned to improvised. Previous planning is fundamental for facing an extreme event, but it is necessary to collect data in order to understand how an organization and its decision making nodes react, especially when they must respond with improvisation because the extreme event was never considered a possibility.

A different approach is presented by Carver and Lesser (1994), who developed the theory of opportunistic planning; this assembles a solution to face extreme events using the library of cognitive and behavioral processes contained within an emergency and response system. This dissertation claims that the roles under a crisis situation do not usually adhere to established procedures for coordination and resource utilization, and many of them present irregular behavior depending on how the situation changes over time.

A key element necessary for modeling organizational behavior facing extreme events is how the data on organizational decision making during emergency response may be captured.

A mathematical approach for the management of emerging phenomena is presented by Guastello (2002), who stated that it is possible to introduce mathematical structures that underlie organizational events and observe some patterns in the way an organization reacts to an extreme event. He proposes *nonlinear dynamical systems theory* for representing organizational behavior and suggests a structural equations technique for testing the nonlinear hypothesis. The Guastello approach matches with the purpose of this research in order to use SD combined with other techniques for simulating dynamic system behavior of different actors who accomplish their tasks over a NCDM environment.

Figure 3 shows a definition of four scenarios regarding events versus location made "to illustrate the range of situations against which potential command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) needs for emergency responders might be identified" (Committee on Army and Technology for Homeland Defense, C4ISR, 2004).

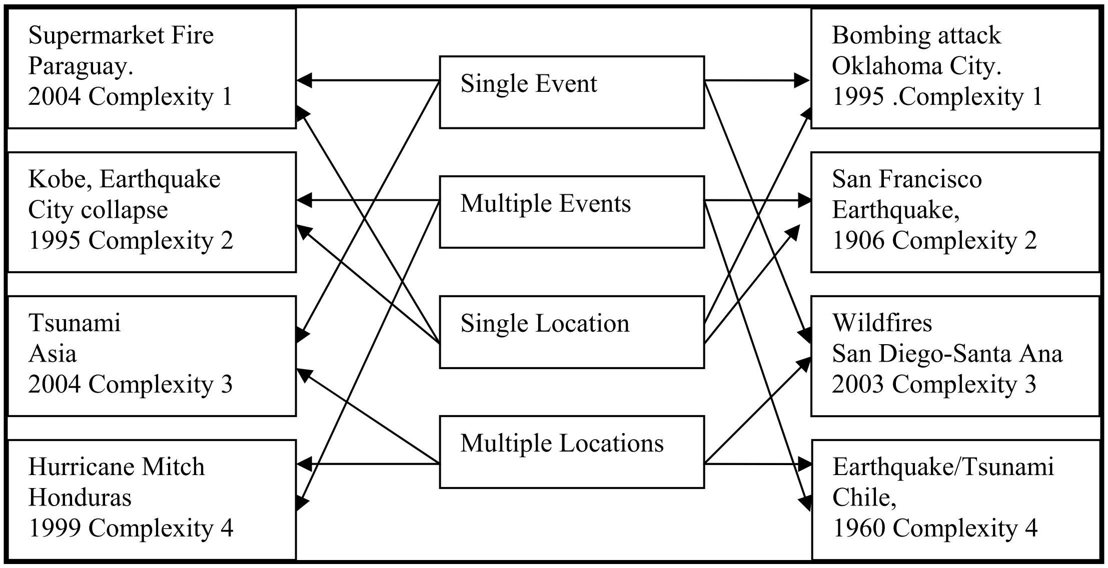


Figure 3: Eight emergency situation area shown with four scenario definitions

The four scenarios previously identified are an initial attempt to develop a parameterized framework which would allow us to quantitatively study a NCDM environment.

Halachmi (1980) stated that several studies have demonstrated that unexpected extreme events within a social system may result in the same patterns of disruptive behavior, even when such events are anticipated. As a consequence of extreme events, he identified two stages: *first order effects* and *second order effects*. The former are direct, unidirectional, and hard to control; they produce changes in organizational behavior, operational behavior, and managerial roles. The latter are the result of multiple interrelations and reciprocal influence, and organization behavior directly affects performance, for instance “during a crisis it is difficult to find a case of an available organization that does not try to play a part in the disaster effort” because it is expected that all roles develop new tasks in response to the disaster which may generate confusion, message overloading, and increasing demand for scarce resources.

Initial requirements for simulating the effects of extreme events produced by terrorism acts were developed by Sandia National Laboratories in 1998. Even though this report considers only terrorism circumstances, it encompasses significant modeling and simulation requirements which could be applied to any sort of extreme event.

According to resounding effects, four scenarios were selected and the corresponding actors, simulation output, and modeling approach are described. All the scenarios require the "interplay and coordination of numerous decision-makers and resources to assist in response and recovery effort." The simulations should be capable of calculating three types of outputs: social impact, economic cost, and organizational effectiveness. The report points out that "a primary use of the model would be to determine the optimum degree of organizational effectives to reduce the social impacts and the economic costs of any incident" (Pryor, Marozas, Allen, Paananen, Hiebert-Dodd & Reinert, 1998).

Smith (2002) presented a related approach that explored the concepts for creating a "simulation of national infrastructure" which could be used to explore the collective impact if some critical infrastructure sector is disrupted by an extreme event. He made a ranking of the most studied critical infrastructures, electrical power being the most studied, followed by telephone systems and water processing. Most of the literature uses the term *extreme events* for referring to terrorist attacks; this dissertation uses the terminology to describe events produced by man-made or natural disasters.

Peerenboom (2002) depicted the implications of multiple contingency events which may affect infrastructures. His main concern is centered on failures affecting the interdependent "systems of systems" infrastructure. Three general category failures are described: cascading failures, escalating failures, and common cause failures.

Modeling and simulating organizational structures

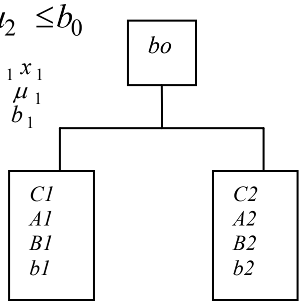
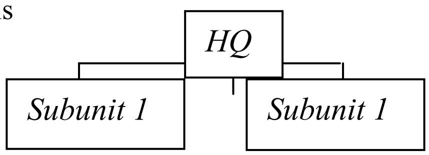
According to most classical research in organizational theory (such as Taylor, Fayol and Weber) it is possible to define the best way an organization could perform in its environment. In contrast to classical scholars, current organizational theorists believe that organizational design depends on the size, technology, strategies, and environment that surround the organization (Borgatti, 2001). The latter approach is known as contingency theory.

In order to define contingency theory, Donaldson (2001) first describes the contingency approach in science, in which the relationship between two variables is part of a larger causal system involving a third variable known as the moderator factor. Thus the focus of the contingency theory" is to study the impact of a third variable on effectiveness and efficiency.

Burton and Obel (1995) summarized the application of mathematics in organizational studies, and they concluded that "information processing is the fundamental way to view organizations and their designs." They defined "the contingency model of organizational design," which makes a relationship between factors for organizational structure and structural configuration of the organization and its properties. The first criteria selected were "effectiveness and efficiency".

Using contingency theory Burton and Obel presented several mathematical programming models of organizational design based on strategy, technology, size, and managerial style. They merged an information processing view of organization with contingency theory, in order to present a combined framework for considering organizational design choice. Table 4 shows the main models supported on classical organizational paradigm and contingency theory.

Table 4: Mathematical programming model (Burton & Obel, 1995)

Model	Implication
$\max \quad K \quad C_1x_1 + C_2x_2$ $A_1x_1 + A_2 \le b_0$ $B_1x_1 \le b_1$ $B_2x_2 \le b_2$	A block-angular structure may model a large organization at two levels. Many emergency structures can be studied by rearranging the rows and columns.
$\mu_1 + \mu_2 \le b_0$ $Max \quad C_1x_1$ $A_1x_1 \le \mu_1$ $B_1x_1 \le b_1$  $Max \quad C_2x_2$ $A_2x_2 \le \mu_2$ $B_2x_2 \le b_2$	Modeling an organizational structure with a headquarters and two divisions. "The mathematical model shows the information interchange in a formal organization. The technique can be applied to multi-level perspective."
Headquarters determine Goals  $Max\,(C_j - \pi I_j)x_1 \qquad Max\,(C_j - \pi A_j)\tilde{x}_j$ $B_1x_1 \le b_1 \qquad \tilde{B}_j\tilde{x}_j \le \tilde{b}_j$	M-form organization modeled with coordination. Most of the examples apply to finance planning or allocation of resources in the industry, but the model fits well for analyzing a combined organization composed of civil, military and non-governmental organizations facing an emergency situation.

In an organizational context, it is usually difficult for decision makers to evaluate the performance of similar units; likely the most successful models have been those known as data envelopment analysis (DEA), which was introduced in 1978. The main purpose of DEA is to evaluate the performance of similar decision making units (DMU) with the same goals and objectives (Anderson, Sweeney & Williams, 2000). Using the previous approach, Zhu (2003) developed new DEA models for evaluating value chains and congestion measures.

Based on a classical organizational paradigm, Virtual Design Team was one of the first simulations which incorporated a hybrid environment to study the total duration of a complete project along the critical path by means of sub tasking. The central idea of the Virtual Design Team was essentially "information-processing structures and communication systems." The models were built under the paradigm of DES and "qualitative reasoning concepts derived from artificial intelligence" (Levitt, Cohen, Kunz, Nass, Christiansen & Jin, 1994).

This dissertation makes a distinction between simulation systems that allow for the collection of data directly from real people (organization in the loop) and those implemented as synthetic entities based on classical paradigms such as discrete simulation, agent-based simulation, or cognitive architectures.

Constructive simulation has been one of the most classical systems for simulating organizational structures, usually used for training military commanders and their staff. According to the Department of Defense glossary (DoD), (1995), this type of simulation means **"**models and simulations that involve simulated people operating simulated systems. Real people stimulate (make inputs to) such simulations, but they are not involved in determining the outcomes". These sorts of simulations were the first attempts to improve organizational behavior in a military context, in particular those performed by the commanders and their military staffs. *Even though constructive simulations are very useful for testing planning and execution, the data acquired from these simulations is produced by the models and not by human behavior*.

MacMillan, Dirdrich, Entin and Serfaty (2005) completed a research project called "Measuring Organizational Performance in Simulation Environment." They provide examples regarding the use of theories and constructive simulations to structure empirical data collection for organizational performance. They focus their research on organizational structures for military command and control, including new structures associated with the concept of NCW.

From this work, the author selected six meaningful findings which confirm the approach of this dissertation:

- Computational organizational models can make predictions about the performance of organizations that do not yet exist.
- Controlled experimentation and correlation studies are severely limited in their ability to consider dynamic causal effect over time.
- Models can act as dynamic theories or dynamic hypotheses by making testable predictions about how multiple variables will interact to produce measurable outcomes.
- At the heart of NCW is the challenge of creating new organizational forms and structures that can use the rapid movement of information to create and maintain a strategic and tactical advantage in military conflicts.
- “The creation and use of constructive simulations to test new organizational concepts does not free us from the need to collect data through empirical human-in-the-loop testing”.

The US Navy Tactical Decision Making under Stress (TADMUS) Program has been the most significant research so far in the area of decision making under stress, considering the issue of how individuals and teams are required to make critical decisions during changing and intense situations (TADMUS Report, 1998). TADMUS was the product of two critical events: the first was the USS Stark incident, where the commander did not engage an inbound aircraft which was not thought to be a threat to his ship, and 27 US naval personnel lost their lives. The second one was the USS Vincennes event, where the commander ordered his crew to engage the inbound aircraft which turned out to be a commercial airline and all personnel aboard were killed (TADMUS Report, 1998).

In 1999 the US Navy published the main benefits from transitioning the TADMUS products and process to other types of civilian and military organizations that must execute their tasks in a collaborative environment, with little reaction time and facing critical decisions. The TADMUS report identified potential advantages to other organizations:

> Many operational environments have the same characteristics as Navy environments. Specifically, information from multiple sources must be processed quickly, events are fast-paced, situations are constantly changing, requiring acute situational awareness and the ability to make decisions quickly in the midst of seeming chaos, decisions can have major impacts (life or death), and teams of experts from various locations and agencies are formed on site and must quickly learn to function as one expert team (TADMUS, 1998).

Even though this dissertation will not incorporate cognitive task analysis, some results tested and validated by the TADMUS Project will be used as a basis for modeling an organizational structure to manage emergency situations.

An experiment was conducted using a synthetic environment reported to investigate the complexities of distributed team interaction and problem solving performance within a controlled setting (Fiores, Cuevas, Scielzo & Salas, 1999). Training performed with 25 undergraduate students allowed the testing of hypotheses regarding problem solving measures and general metacomprehension. The study found that multiple computer-based methods of diagnosing problem solving performance can be used to assess knowledge acquisition for a complex synthetic team task.

Supported by these hypotheses, a novel methodology, designed by the Chilean Army and known as Training Organizational Behavior, was implemented by means of a collaborative software known as Simulation for Training Emergency Response, a web-based training system whose main purpose is to produce data to evaluate organizational behavior when critical decisions are to be made and response time is limited (SIGEN Project, 2003). This methodology has been used in the training of more than 120 users that belong to civilian and military organizations, including an emergency system for Honduras facing an event similar to Hurricane Mitch, an emergency system for Chile facing an earthquake, and a peacekeeping operations battalion posted in Haiti. Although the system enables the improvement of collaborative decision making as a whole, individual behavior and information path analysis is still hard and time-consuming for analyzing and determining the cause-effect relationship between decisions made in different roles.

Lin (1994) argued that “often, success is not guaranteed by the existence of a complex organization design nor by the existence of high-quality information alone.” His research showed that an organization with a high performance level must have an organizational design matched to the task environment, and he concluded that the best design is contingent.

Yasuhiko (2004) in a novel study defined an organization as “a complex system of interconnected human and nonliving machines” (Notice that the definition is comparable to a net-centric environment, previously described in this dissertation). In their research they identify two approaches to develop formal results for an organization: The first one is named “qualitative mathematics or organizational cybernetic theory” and the second one is named “computational approach.” Table 5 summarizes the two approaches.

Table 5: Contrast between two approaches for modeling organizations (Yasuhiko, 2004)

	Organizational Cybernetic Theory	Computational Organizational Theory
Internal Structure	Three layers, each one with very well defined functions.	Less structure, there is a collection of processes and intelligent adaptive agents with a dynamic behavior.
Components	• Goal-seeking object • Goal-seeking activity (optimization, coordination, and adaptation according to its hierarchical position). • Process model	• Agents • Tasks • Skills
Methodology	Mathematical qualitative approach.	Simulation, expert system, and numerical analysis.
Research Area	Organizational design.	Organizational design and learning, organizational and information technology, organizational evolution and change.
Constraints	Implicitly handled as constraints to a goal-seeking activity.	Explicitly defined.

Social networks

A social network is a set of actors that may have relationships with one another. Networks can have few or many actors (nodes), and one or more kinds of relations (edges) between pairs of actors (Hannemann & Riddle, 2005). The use of a network for representing mathematical relationships among entities was started in the 17th century when Spinoza developed the first model. In 1937 Moreno introduced sociometry and sociograms and in 1948 Bavelas founded the group networks laboratory at MIT. The concept of centrality was specified at this time and in 1949 Rapaport developed a probability-based model of information flow. In the 1970s the social field emerged based on new features in graph theory and computational analysis of complex data sets (Freeman, 2000).

Based on SNA, Carley (1995; 1999) described the concept of *computational organization analysis* in which the organizations are viewed as inherently computational entities and she defined a set of key measurements for characterizing organizational architectures. Carley has developed significant contributions in the area of dynamic social networks, most of them supported by mathematical foundation and computational analysis.

In order to design the best possible C2 architectures for the Australian Defense Force, FINC (Force, Intelligence, Networking, and C2) methodology was implemented based on a social network foundation. The method allows the calculation of three metrics for every C2 architecture: the information flow coefficient measuring tempo superiority, the coordination coefficient measuring coordination superiority, and the intelligence coefficient measuring information superiority. Based on a test-bed, it was possible to explore the impact of different organizational architecture under a range of different conditions (Dekkler, 2002).

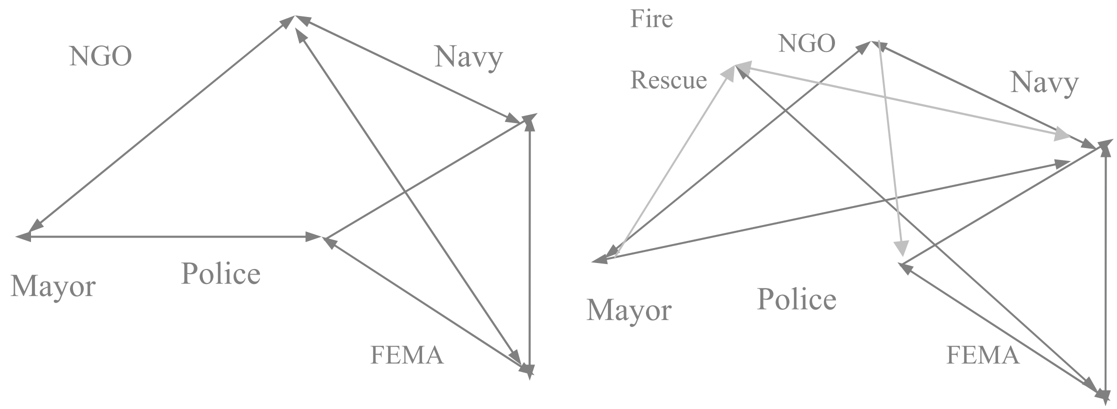
Similar experiments have been developed at the Center for Computational Analysis of Social and Organizational Systems at Carnegie Mellon University. One of the most representative deals with "Measuring and Modeling Change in C3I Architectures" using PCANSS formalism, mathematically represented C2 architecture as a set of matrixes linking personnel, resources, tasks, and relations among them. Results pointed out the degree of similarity/difference in the various measures, the relative ability to predict performance, and the relative ability to predict adaptability in C2 Architectures (Carley, Ren & Krackhardt, 2001; Hazy & Tivnan, 2004).

Simulation-based statistical inference for the evolution of social networks was presented by Snijders (2004), who asserted that single observations of networks are snapshots and the results of untraceable history, and then the more descriptively oriented type of statistical modeling of linear regression analysis cannot be transplanted to network analysis, where the focus has to be on modeling dependencies.

Extreme events analysis with data coming from real people and real events is expensive and time consuming for implementation. Mendonca and Wallace (2003) describe one of them:

> …interview data from Hurricane Camille, directed graphs were constructed, a total of 52 interviews were analyzed and 106 response personnel in more than 85 organizations identified. Based on social network analysis, the results suggested that among the senders the most central organizations were the Police Department and the Emergency Operating Center; on the other hand, among the receivers the most central organizations were the National Guard and Radio Station. Additionally this analysis incorporated basic matrix operations applied to the adjacency matrix to examine the centrality of the network. The study identified that the Police Department, the National Guard and the Radio Station played central roles as senders since their respective normalized degrees were greatest. These groups can be viewed as the ones that requested the appropriate authority for an update of the situation, announced to the public on the current condition of the Hurricane, and/or declared a curfew/warning….

This dissertation suggests that a social network could be combined with other simulation techniques, allowing the possibility for gathering different snapshots of organization states over time. The merged techniques may be used to describe behaviors of individuals and groups when there are digital systems that allow the logging of communications, tasks, and decisions. Figure 4 shows two states of the evolution of an organization when it faces an extreme event.



	Police	Mayor	Navy	FEMA	NGO	Measures and metric			Police	Mayor	Navy	FEMA	NGO	Fire Rescue
Police	X	1	1	1	0	Degree	Max.Flow.	Police	X	0	1	0	0	0
Mayor	1	X	0	0	1	Mutually Connected nodes.	Noah effect centrality	Mayor	0	X	1	0	1	1
Navy	0	0	X	1	1	Geodesic Paths.	Sequence.	Navy	0	0	X	0	0	1
FEMA	1	0	1	X	1	Dependency.	Cohesion.	FEMA	1	0	0	X	0	1
NGO	0	1	1	1	X	Connectivity (nodes).	Clique.	NGO	1	0	0	0	X	0
								Fire Rescue	0	0	0	1	1	X

Figure 4: Networks and matrix to represent an emergency management organization in two periods

This research requires identification of the main variables and states of an organization over time in order to decide which merged techniques are more suitable for simulating either the variables or the states.

Lorrain and White developed an evolutionary approach for studying structural equivalence in social networks; their work was known as *blockmodeling*, which is characterized by two main aspects

- To provide a way to analyze role structures (positions).
- To allow identification of basic structures of social networks (usually organizational structures with more than 15 roles are difficult to analyze).

In practical aspects blockmodeling seeks to reduce and simplify a large network which could not be well understood. The reduced network can be represented by its relational matrix known as an "image matrix" (Lorrain & White, 1971).

There are several algorithms which are used to assign a block to a subset of data, one of the most well-known is CONCOR (convergence of iterated correlations), which is based on the convergence of iterated calculation of the Pearson correlations of pairs of either rows or columns (Netminer, 2005).

To identify common behavior of actors working in an organization, Schwartz and Sprinzen (1984) identified that,

> the occupant of a common position will exhibit a common pattern of relations, across multiples relations, consistently tending to have certain relations with occupants of particular other positions and to not have the same type of relation with of yet other position".

In order to study transactions in interdependent relations, Buskens (2002) described social networks as a "valued directed graph with weighted nodes." A valued network representing n nodes is a pair (π**,** **A**), where π is a n-vector of weights indicating the importance of each node with $\sum_{i=1}^{n} \pi_i = 1, \pi_i > 0$ for all i, and **A** is a n x n matrix where αij, $0 < \alpha ij < 1$, is the importance of the tie from node *i* to node *j*. Moreover Buskens described "global network parameters which can measure the properties of a network as a whole and can explain interaction networks effects." Several inferences on the effects of network parameters on information diffusion rates are summarized in Table 6 and Table 7. Implications are inferred according to this research.

Table 6: Individual network parameters (TR= Transition rate, RR=Reception rate) (Buskens, 2002)

Individual	Network Parameters	TR	RR	Implication for NCDM
Out-degree	$D_{out}(i) = \frac{1}{1-\pi_i}\sum_{j\neq i} \pi_i \alpha_{ij}$	+	0	Nodes with higher out degree could send more information and generate less uncertainty for situation awareness.
In- degree	$D_{in}(i) = \frac{1}{1-\pi_i}\sum_{j\neq i} \pi_i \alpha_{ji}$	0	+	Nodes with higher in degree receive more information, likely more congestion, require more analysis.
Out degree Quality	$Q_{out}(i) = F(\pi, D_{out}, \alpha)$	+	0	Depend on network position. This parameter shows the extent to which a node is linked to nodes which have high degree themselves. We suppose higher degree quality could increase the transmission of information but could be dangerous if the initial or bridge nodes are critical points into a NCDM environment.
In-degree Quality	$Q_{in}(i) = F(\pi, D_{out}, \alpha,)$	0	+	If one node receives information from one node it receives partial information if the sender node receives information from only one node. Extreme consequence for decision makers if this node does not have certain autonomy.
Local out degree density	$LD_{out}(i) = F(\pi, \alpha)$			This parameter measures the extent to which a node transmits information to connected neighbors. In a NCDM environment it could be expected that information is transmitted more slowly if a node informs two nodes which have many contacts between themselves.
Local in degree density	$LD_{in}(i) = F(\pi, \alpha)$			This parameter measures the extent to which a node obtains information from connected neighbors. Likely nodes with higher in degrees will receive information sooner than nodes with lower local in degree.

Table 7: Global network parameters (TR= Transition rate, RR=Reception rate; Buskens, 2002)

Global Network Parameters	Network Parameters	TR	RR	Implication for NCDM
Density	$\Delta = \frac{\sum_{i=1}^{n}\sum_{j\neq i}\pi_i\pi_j\alpha_{ij}}{\sum_{i=1}\sum_{j\neq 1}\pi_i\pi_j}$	+	+	Working on network centric environment. Could information be transmitted faster on networks with higher density?
Out degree variance	$V_{OUT}=\sum_{i=1}^{n}\pi_i\left(D_{OUT}-\sum_{j=1}^{n}\pi_J D_{OUT}(J)\right)^2$	-	-	Average variance in the out degrees nodes in the network. Centralization could accelerate information diffusion if the central nodes are important in the diffusion process.
In-degree variance	$V_{IN}=\sum_{i=1}^{n}\pi_i\left(D_{IN}-\sum_{j=1}^{n}\pi_J D_{IN}(J)\right)^2$	-	-	Average variance in the in degree nodes in the network. Centralization could accelerate information diffusion if the central nodes are important in the diffusion process.
Out-degree/ In degree variance	$V_{IN,IN}=\sum_{i=1}^{n}\pi_i\left(D_{IN}-\sum_{j=1}^{n}\pi_J D_{IN}(J)\right)*\left(D_{IN}-\sum_{j=1}^{n}\pi_J D_{IN}(J)\right)$	+	+	There are not clear inferences for centralization parameters; Buskens argues that likely the "information transmission rate and the information reception rate decrease with out degree and in degree variance." Note that this analysis is a "conjecture" in a social network environment; we are exploring possible tools for analysis in a NCDM environment.
Network Size	N			Network size, because Buskens defines $\pi i = 1/n$ then the numbers of nodes can have effects on information diffusion.

Carley (2003; 2005) introduced the concept of dynamic network analysis, and she pointed out that "traditionally SNA has focused on small, bounded networks, with 2-3 types of links among one type of node at one point in time, with close to perfect information." Dynamic network can deal with large dynamic multi-mode, multi-link networks with variable levels of uncertainty. Her analysis is based on three key innovations:

- Meta-matrix – Focusing on people, knowledge-resources and tasks.
- Probabilistic ties – The links in the meta-matrix are probabilistic.
- Multi-agent network model – Using basic social and cognitive processes people can learn, do tasks and take part in events.

Carley's approach is an attempt to define a new theory named Dynamic network analysis, and her analysis is supported in numerous previous papers and toolkits such as PCANS, DyNet, and OrgNet. (Carley & Kanmeva, 2004)

Discrete event simulation

In DES passive objects represent entities, which travel through the blocks of the flowchart and wait for getting a service. The literature shows few examples regarding studies of organization structures from a DES perspective. One of the main advantages of DES for modeling organizational structures is that it enables parallel, distributed, and interdependent organizational traffic flow across the network to be accurately simulated (Griffin & Skinner, 2003). Moreover, DES enables tracking the status of individual entities in a shop floor (organizational structure) and estimates numerous performance measures associated with those entities (Venkateswaran, Son & Jones, 2004).

On the other hand DES simulation is not appropriate when state variables interact with one another on a continuous basis, and when entities and their internal mechanisms are a more important element of the simulation than an event, per se (Dooley, 2002). There are significant elements which are appropriate for modeling organizational structures, although this technique is not enough for gathering all the characteristics of an organization.

A DES simulation approach was used for modeling the critical decisions timeline performed by the crew of the USS Vincennes (Franceschini, McBride, & Sheldon, 2001). We estimate that significant activities performed by an emergency organizational structure can be modeled and simulated with DES, such as workload, priorities, saturation, timeline, service time, etc.

A different perspective is presented by McGinnis (2005) who explored the concept of organizational simulation using the knowledge acquired from two domains: integrated circuits (ICs) design and discrete event logistics systems. He said "in terms of design features, a contemporary IC is clearly a more complex artifact than could be contemplated." ICs have many levels of abstractions in which at the lower level there is a small set of bases and simple functions, and thus very precise simulation models can be compiled and can predict behavior. Very High Speed Integrated Circuit (VHSIC) Hardware Description Language is the technology which enables design automation for digital ICs.

However, a discrete event logistics system is not a completely formalized process and there is an absence of a formal modeling discipline (ad hoc discipline). As McGinnis (2005) notes, "Nevertheless a large portion of the organizational simulation problem domain consists of organizations which exhibit discrete flow of materials, people, or information, and whose behavior over time is intimately related to these flows.".

Biswas and Merchawi (2000) reported the implementation of a discrete simulation model in conjunction with an agent based scheduling engine. Their implementation enabled validation of an adaptive scheduling using a discrete simulation software package in which several factories are simulated. Controlled input parameters were sent through of a message broker to an *agent based scheduler* in which several agents make decisions based on their own individual priorities and rules.

On the other hand, Venkateswaran, Son and Jones (2004) modeled a *hierarchical production planning* using two levels, the first one named *planning* (higher decision level) and the second named *scheduling* (lower decision level). A SD model simulated "the production dynamics involved in the execution of the production plan," and a DES model simulated the operations carried out in the enterprise such as material processing, transfer, and storage. The interaction between SD and DES was made via a *high level architecture*. The results demonstrated that the hybrid simulation framework provides seamless integration between SD and DES models and can be used to analyze interdependency between planning and the manufacturing processes in an organization.

The two previous examples show the integration of two simulation paradigms in a manufacturing environment, and both applications enclose significant techniques which could be customized for simulating a network-centric process.

Searching by organizational structures which perform their tasks over a network-centric environment, this literature review summarizes the most complex model found based on a DES named "A Study on the US Expeditionary Warfare System." The study was conducted at the Naval Postgraduate School and the model basically emulates an expeditionary force which is defined as a system of systems where ships, aircraft, vehicles, fuel, food, water and so on are linked on a network-centric environment. The simulation enabled the evaluation of three issues:

- A system of systems analysis for a expeditionary warfare architecture.
- The study of interfaces and synergies among ships, aircraft and systems within architecture.
- The comparison of different operational concepts in terms of troops, vehicles and logistics support.

Even though the two models built provided significant knowledge about how to analyze a military organization in a dynamic environment, this simulation has some limitations: Some steps require user inputs; there is a constant rate of consumption based only on vehicles and troops; the simulation does not produce the best solution, and there are no optimization modules in the system; and finally, the assets and resources are generalized into different categories (Students of the US Naval Postgraduate School, 2003).

The Network Warfare Simulation is a discrete event simulation tool built under a net-centric approach. The system allows the simulation of voice and data communication required during civil and military crisis events. The architecture is supported by commercial off-the-shelf software, and is made up of a set of libraries, a scenario builder, planning capacity, a simulation engine, and analysis tools. Simulation can be used to model communication equipment, organizations, and information (Flournoy & Murphy, 2002).

System dynamics

The basis concept in SD is that behavior of a system arises from its structure. In system dynamics this structure is modeled based on feedback loops, stocks, and flows (Sterman, 2000). Much of the literature points out that SD is a technique for dealing with complex systems because nonlinearity emerges as the most common behavior. Mathematically, an SD model is a system of differential equations, in which the model works only with aggregates. The items in the same stock are indistinguishable and there is a global structural dependency (Borshchev & Filippov, 2003).

In order to describe a problem in SD, the modeler has to show the system's behavior as a number of interacting feedback loops, balancing or reinforcing. The system's behavior must be first generalized from specific events associated with the system under study, and it requires investigation as to how the variables change over time. Therefore, when the behavior is known, the modeler can look for the system structure which is the cause of the behavior. Usually the systems present four types of behavior patterns and each is generated by different structures. Tables 8, 9, and 10 show these behavior patterns (Kirkwood, 1998, Sterman, 2000).

Table 8: Positive feedback loop (modifications to Sterman, 2000; Kirkwood, 1998)

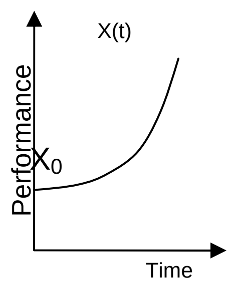
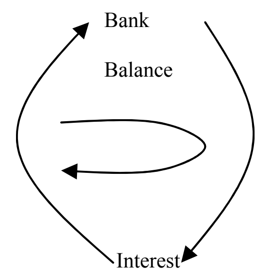
Pattern behavior	Analytical solution	System Structure
	$\frac{dx(t)}{dt} = g \cdot x(t)$ $x(t) =$ Stock variable x at time t. $g =$ growth rate (g>0) $x(t=0) = x_0$ $x(t) = x_0 \cdot e^{g \cdot t}$	

Table 9: Combination of positive and negative loops (modifications to Sterman 2000; Kirkwood, 1998)

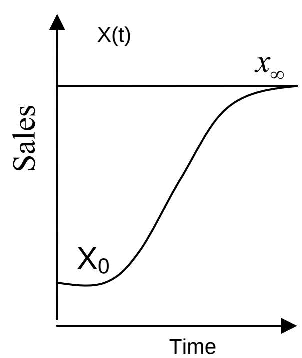
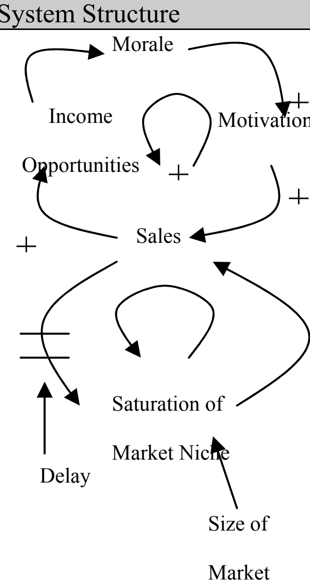
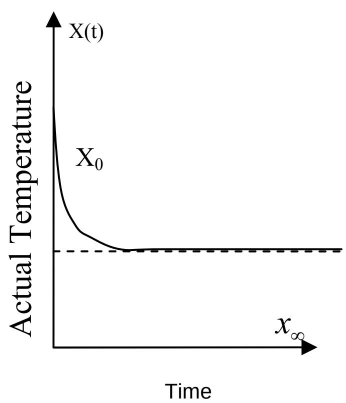
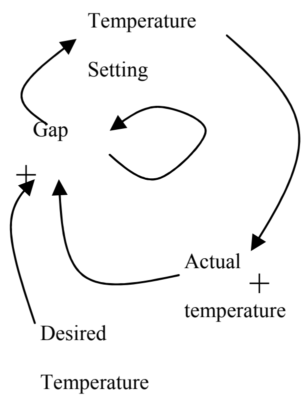
Pattern behavior	Analytical solution	System Structure
	$\frac{dx(t)}{dt} = g \cdot \left[1 - \frac{x(t)}{x_\infty}\right] \cdot x(t)$ $x(t) =$ stock variable x at time t $x_\infty =$ stock limit of variable x(t) when t tends to be infinite $g =$ maximum fractional growth (g>0 assuming that $x(t=0) = x_0$, the solution to the former equation is: $x(t) = \frac{x_\infty}{1 + \left[\frac{x_\infty}{x_0} - 1\right] \cdot e^{-g \cdot t}}$	

Table 10: Negative feedback loop (modifications to Sterman 2000; Kirkwood, 1998)

Pattern behavior	Analytical solution	System Structure
Negative (balancing) feedback loop. 	$\frac{dx(t)}{dt} = \beta \cdot [x_\infty - x(t)]$ $x(t) =$ stock variable x at time t $\beta =$ growth rate (β >0) x_∞ = limit x(t) when t→ ∞ $x(t=0) = x_0$ $x(t) = x_\infty - [x_\infty - x_0] \cdot e^{-\beta \cdot t}$	

In order to build a SD model, a modeler breaks down a known process into distinct stages and represents the interactions between the various stages. Such models are called "compartmental" and are graphically depicted by block diagrams (Nagle, Saff & Snider, 2004).

In the early 80s, Coyle (1980) published a model about "The Dynamic of the Third World War," which represents a hypothetical war between NATO and the Warsaw Pact. Although it is recognized that SD technique allows aggregate modeling (high abstraction for policy), the model showed real parameters combined with different strategies in a specific timeframe. Resources, vehicles, weapons, and forces were also incorporated into the model. Three main conclusions arose:

- The model was an aid to understanding structures.
- It was proposed as a tool for analyzing contingency planning.
- It was identified as a decision support at the heart of a C2 System.

Twenty years later, SD simulation technique continues being used (beyond the business arena). For instance, Sandia Laboratory analysts have created several models to combine generic components of specific systems in order to simulate domestic infrastructure protection. “Their goal is to create a modeling structure and software module that can capture the interdependencies” between critical infrastructure (Smith, 2002).

Yerkes and Dodson (1908) developed a curvilinear relationship between stress and performance known as “Yerkes-Dodson Law of Arousal”, which states that an organism’s performance can be improved if this organism is aroused in some manner. However, if the level of arousal increases too much, the level of performance decreases. Using the previous relationship as an assumption, Rudolph and Repenning (2003) implemented a SD model to study how organizations react to an ongoing stream of interruption of normal activities; they demonstrated a new crisis archetype, the quantity-induced crisis. Their study suggests that the strategies often proposed for mitigating a novelty-induced crisis – stepping back and reframing the situation – can be counterproductive when confronting a potential quality-induced crisis. As shown in Figure 5, any action that temporarily slows the interruption resolution rate can push the system closer to an unstable equilibrium, making collapse more likely.

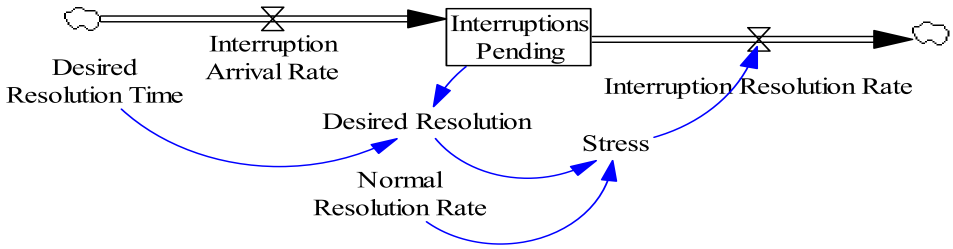


Figure 5: Structure of disaster model (model developed for this dissertation, following the facsimile of Rudolph et al., 2003)

Agent based modeling

There is no universal definition to describe the ABM paradigm, and people are still discussing what type of properties an *agent* must have to deserve this label (Borshchev & Filippov, 2004). This literature review enabled the collection of several attributes which could characterize a piece of software named *agent*: decentralized behavior, learning from experience, bottom-up modeling, global behavior emerging from many individual entities, demonstration of some degree of intelligence, perception of the environment and that influence reactions, capacity for interaction, and social ability.

The agent definition which more faithfully represents the objectives of this research: "Agents are programmed software modules that scan their environment and make a decision" (Ilanchinski, 1996).

From an academic perspective, Wooldridge (2002) presented abstract architectures of intelligent agents; his main contribution is the "formalized view of agents." Initially he defined the surrounding agents' environment which is based on a finite set of discrete states (E={ *e', e'',*

$,e'''...\}$). The agents "are assumed to have a repertoire of possible actions available to them which transform the state of the environment" ($Ac=\{,\alpha', \alpha'', \alpha''' ...\}$).

Interaction is produced when the agent chooses an action α to perform on $E= e$. Then the E responds with a number of possible states e; nevertheless the agent "does not know in advance" which will be the future state. Thus new cycles can be executed.

In the context of this research, we consider significant three attributes defined by Wooldridge:

- Agents are assumed to be deterministic.
- The environment is history dependent and implicitly non-deterministic.
- Agents make decisions about what action to perform based on the history of the system.

This literature review found few examples regarding applications of ABM to organizational structure analysis, and we are going to concentrate on those which combine two or more simulation techniques.

TalenSim is a prototype based on the SD and ABM paradigms. It enabled the implementation of different scenarios with respect to organizational transformations and their impact "on workforce without any of the real-world consequences such as lower performance, turnover, low organizational commitment, etc." Three entity types are modeled in the simulation: environment, company, and individual (Prasad & Chartier, 1999).

Qudrat-Ullah (2005) pointed out that SD validation techniques can be applied to ABM. He argued that there are three strong similarities between both techniques:

- They can model non-linear and complex systems.
- Both assume that micro-structures of a system are responsible for its behavior.
- Both aim at discovering the leverage point in complex systems.

Kang, Waisel and Wallace (1998) used computational modeling with distributed artificial intelligence as a paradigm for studying team behavior. The architecture that they chose was TeamSoar, which enabled the interconnection of individual agents. A naval command and control team was modeled and simulated and its results indicated that simulation is adequate for studying teams and predictions can be obtained regarding what happened.

Even though computational models are useful for analyzing team decision making, those teams are made up of few nodes (4 nodes were described by Kang et al.) and tasks are strongly linked to the environment in which the team executes its mission.

Borshchev et al. (2004) presented a methodology for transforming SD and DES models into an ABM: The idea behind this approach is to simulate more sophisticated behavior using the statechart design. This approach is congruent with the Prasad application named TalenSim developed four years before. Statechart design is based on state machines adopted as a part of the standard Unified Modeling Languages (UML). Statechart enables the capturing of different state transitions of agents, communication among them, and actions which are performed by each one (agents). According to Borschev et al., using statechart it is possible to “re-conceptualize” existing SD and DES models.

The previous statement does not mean that the ABM approach is a replacement for SD or DES; there are a lot of applications where both simulations fit very well to solve real life problems. Moreover, for many such applications, ABM will not make much sense, being less efficient, harder to develop, or simply not matching the nature of the problem.

After analyzing this technique based on Unified Modeling Languages-Real Time, this literature review found useful features for modeling an emergency organizational structure by linking the concepts of ABM and statechart.

In order to generate understanding and inform research into the dynamics of cellular receptors, a study was conducted to compare SD and ABM. The comparison measured the overall approach, the underlying mathematics and analysis, the easiness with which results can be communicated to others, research relevance, and educational potential. The results showed that SD is more conceptual than ABM and the modeler should be careful to select the appropriate level of aggregation. Nevertheless SD is easier to implement and to conduct sensitivity analysis. On the other hand, ABM obligates the modeler to describe clearly the definition of agent and also the modeler needs to specify the rules which will control the agent's behavior (Wakeland, Gallaher, Macovsky & Aktipis, 2004).

Even though SD is a relatively high level technique (aggregation), it presents difficulties for identifying stocks and flows in a system such as an emergency organization structure. This problem becomes fundamental if we want to model the reality into a synthetic environment.

In contrast, SD provides the capacity for modeling "non-linearity" based on feedback cycles and delay functions, aspects that could be useful for modeling organizational behavior over a networked structure.

Conclusion based upon literature review for "Modeling and Simulating a Network-Centric Scenario under Extreme Events"

Based on the literature review, this research proposes and justifies the use of mathematical and simulation techniques for developing a digital network-centric environment in which generic organizations could validate, study, and predict organizational behavior under extreme events. The term "generic organizations" is used to represent civilian, military, humanitarian, non governmental organizations (NGO), or merged organizations which perform their tasks over a collaborative scenario, in separate locations and where each one has clear procedures for dealing with the information. Note that a “generic organization” interacts over a communicational infrastructure where many devices present individual and collective behaviors, such as databases, sensors, hubs, and decision support systems.

In this step, some people could ask “why does this research incorporate a SNA and not consider graph theory?” The answer is simple: SNA has its foundation in graph theory, and researchers have found many findings supported by graphs. Therefore, we make use of their interpretations to analyze a network centric environment.

Table 11 presents the main characteristics of the three main simulation paradigms and SNA. The table merges the findings of Chapter Two with our experience using the named techniques.

Table 11: Comparison of SD, DES, ABM and SNA

	System Dynamics	Discrete Event Simulation	Agent Based Modeling	Social Network
1. Level	Appropriate for modeling the aggregate behavior resulting from effects (non interactions) among multiple types of categories.	Appropriate for modeling details, known processes and different entities and levels.	Appropriate for modeling movement and state changes of individual entities, their interactions and rules. Implementing different levels.	Appropriated for predicting future layout. Appropriated for analyzing topological structures.
2. Entities	Undistinguished, only dimensions and categories.	Distinguished entities.	Distinguished entities with interaction but usually there are not transactions.	Distinguished nodes, but there are not transactions among them.
3. Best use	Efficient for modeling large number of continuum interactions.	Efficient for modeling large number of discrete transactions and processes.	Inefficient for modeling large numbers of interactions.	No interactions for modeling. Inefficient for large network analysis, requires "complex network analysis" technique.
4. Parameters	Parameters cannot be modeled in different levels.	Parameters can interact in different levels.	Micro and macro parameters can interact. Vertical influence.	Parameters cannot be modeled in different levels.
5. Actions	Level and flow cannot represent actions.	Can implement rules but not actions.	Actions allow generating behavior.	Nodes and ties cannot represent actions.
6. Internal structure	Good for showing system's structure and numerical results.	Good for capturing processes and measuring performance.	Good for showing the behavior of individual entities. Difficult to implement structure; it emerges naturally.	Good for display topology and relationship between nodes. (dependencies, connections, centrality, cohesion, equivalency)
7. Mathematic	Numerical integration of difference equations. Stochastic processes	Queuing theory and stochastic processes.	Logic, algorithms, and probabilities.	Graph theory and structural analysis.
8. Abstraction	Abstract, via state variables and equations that are solved to simulate behavior over time.	Realistic, entities travel through several paths, server process, transform and sent to another server.	Physical emulation of "agents" whose rules for behavior mirror the real world.	Realistic and observable. Easy to implement physical emulation of locations and relationships.
9. Behavior	Difficult to identify unique behavior at the entity level.	Easy to identify behavior at the entity level.	Easy to identify unique entity behavior.	No behavior is shown.

	System Dynamics	Discrete Event Simulation	Agent Based Modeling	Social Network
10. Systems' understanding	Useful for increasing conceptual understanding.	The system must be known before modeling. Does not increase conceptual understanding.	Useful for understanding interactions and global behavior, but it requires a previous conceptual understanding.	Requires a well known layout, based on location, and relationships. System's properties must be emulated.
11. Inaccuracy	Modeler can easily define a high level of aggregation which may not be adequate for simulating a system.	Modeler easily can define the right physical layout for simulating a system.	Modeler must consider the definition of agents in the right level. Selecting the adequate rules and interaction could be a possible source of mistakes.	Two sources of mistake could be found: Input data set and Data interpretation. Requires knowledge of the system under study.
12. Data Inputs	Does not require exhaustive data collection. Requires right empirical evidence and right input parameters.	Requires exhaustive data collection and accurate distribution probabilities.	Requires observable rules and interactions with the environment.	Requires exhaustive data collection, which makes for difficult identifying and collecting.
13. Data outputs	Many outputs; if the empirical evidence (policies) is modeled using wrong parameters the outputs will be worthless. Notice, outputs are tendencies (policies). For current methodology, it is not allowed to apply statistical analysis.	Many outputs, statistical analysis is required. Good for performance analysis.	Many outputs, difficult to select the right measurement of performance.	Outputs are new metrics deduced from new configurations, nodes size, ties and positions.
14. Validation	Validation could be easy if it is implemented at a high aggregated level. Hard if the aggregate level presents many parameters or there is a high level of abstraction. No calibration.	Depending on the simulated system and historic data available.	Available information does not enable a conclusive answer.	Yes

	System Dynamics	Discrete Event Simulation	Agent Based Modeling	Social Network
15. Intelligence	No	No	Yes, but the modeler must specify what type of “intelligence.”	No
16. Sensitivity Analysis	Well situated for sensitivity analysis.	Better situated with DOE.	No information available.	Yes
17. Optimization	No	No	No	No
18. Dynamics Changes	No.	No.	Yes.	No.

Twenty one significant conclusions are derived from the literature review:

- Currently there are no models which use a hybrid simulation technique to represent the performance of an organization structure under an extreme event. The few models are based on linear programming and ABM.
- General simulations based on quantitative techniques are either scarce or poorly documented. Mendonca and Wallace (2003) reported an analysis of Hurricane Camille using a SNA technique; Doreian et al. (2005) used the same technique for analyzing “Interorganizational SAR Network” formed after a small tornado flipped a boat on Lake Pomona in Kansas.
- The USS Vincennes' incident and “A Study on the US Expeditionary Warfare System” are the only research efforts which mention the use of DES technique for simulating an organization.
- Data output collected from either training systems (those which the author named “organization in the loop”) or real systems such as C2 is not used for implementing a

"synthetic organization in the loop." In the past, researchers have preferred to implement synthetic entities based on cognitive architectures.

- Organizational in the loop, C2 systems, and surveys are the only means for collecting real data.
- Most of the analysis found is performed in laboratories for testing hypothesis about team performance and cognitive task analysis, but usually does not involve real people with their real roles, working on the real organization structures facing real threats. This research is based on real organization structures, and the data input collected comes from digital training exercises and case analysis.
- The literature does not show any operational system which allows implementing the AAR based on quantitative analysis.
- The network centric environment presents characteristics which could be applied to military or civilian organizations facing extreme events, and this environment could be modeled using traditional simulation techniques. This dissertation argues that "technological organizations walk toward a network-centric environment" (Organization structures for dealing with extreme events are technological organizations).
- In the content for modeling network-centric environment, the literature review found significant studies whose purposes are modeling and simulating some aspects of a network centric process. Most of these studies use DES.
- The contingency theory provides a framework for modeling NCDM since it supports the concept that organizational designs must be in accordance with the contingency environment.

- Extreme events should be modeled in their consequences for critical infrastructure and their disruptive effects over emergency management.
- Mathematical programming and SNA fit well enough for evaluating organizations before facing extreme events.
- DOE could be a useful technique for improving organizational behavior.
- The literature review found few examples about combined applications of SD-DES and SD-ABM.
- In the context of emergency response, the literature review found few examples regarding to applications of SD, DES, ABM and SNA.
- In two older studies SNA was used for representing a small emergency organization's response. The Australian Army has experimented modeling a network-centric environment with SNA technique.
- Guastello (2002) proposed NDS for modeling organizational reactions to extreme events; this idea is in accordance with the objectives of this dissertation.
- Sandia Laboratories works with SD techniques for analyzing vulnerabilities of critical infrastructure.
- Dynamic network analysis is a novel technique, which does not consider the traditional simulation paradigm, even though it is based on SNA technique.
- There is no concrete definition of agent based simulation. Two possible definitions of agents are: "emergent behavior arises from microscopic entities" and "entities which present some degree of intelligence."

Past research efforts and comparisons shown in Table 11 enable us to build dynamic hypotheses for evaluating different configurations and circumstances in which organizations face extreme events.

Gaps identified in the literature

Table 12 shows the area in which this research will be conducted and describes other research efforts evaluated at the present time.

Table 12: Research gaps relevant to this dissertation

Simulation technique	Planning and Decision Support	Command and Control Systems	Network Centric Decision Making
Social network analysis	Carley Mendonca & Wallace CASOS, CMU.	Carley, Ren, & Krackhardt, 2001 Mendonca & Wallace, 2003 CASOS. CMU. Care, 2005	Dekker,2002 Care, 2005.
Systems dynamics	Sterman,2000. Coyle, 1980. Sandia Laboratories. Smith, 2002.	Literature does not describe examples. The author assumes confidential information.	GAP
Discrete events simulation	Student of the US Naval Postgraduate School, 2003.	Franceschine et al. 2001.	Hazen & Fewell, 2004.
Agent based modeling	Many researches and models	Research without validation	GAP
Hybrid simulation	Venkateswaran et al. 2004.	Literature does not describe examples. The author assumes confidential information.	GAP - Current research

CHAPTER THREE: METHODOLOGY AND SEMANTIC ANALYSIS OF EXTREME EVENTS

Introduction

This chapter provides the methodology we will use to conduct this research in order to map real entities into a simulated environment using the three main simulation paradigms combined with social network technique.

The literature review identified a consensus among researchers that complex systems can be modeled making certain abstractions regarding the entire system details but capturing the aspects that have more influence in the system's behavior.

We apply the previous assertion, since a networked environment is a complex system where a structured organization must deal with many tasks and uncertainties due to the nature of the extreme events, which makes it impossible to model and simulate a complete scenario with a high level of detail.

Making certain abstractions regarding the characteristics of the extreme events, we will concentrate our research on the structure of the organization and its flows, since those elements usually are very well defined in the plans and system reactions of the organization. Processes, procedures, messages, synchronization, and metrics for assessment are the key elements to be simulated and studied in a hybrid simulation platform.

We will use the term "nodes" to refer to the agents who integrate an emergency organization; such nodes can be human beings or machines, both integrated over only one system of prevention and mitigation of extreme events. Examples of nodes are command posts, managers who manage facilities, sensors such as radar or satellites images, sensors such as tsunami warning alerts, or a commander and his staff.

The existence of a plan, such as the Emergency Operations Plan described in National Incident Management System (NIMS, 2004), is significant for making some hypotheses regarding the future performance of the organization. This research identifies the initial configuration of an organization as a structure composed by nodes, connections, resources, tasks, and several procedures which are fired depending of the type of extreme event.

The evolution of an extreme event causes the structure of the organization to change. Therefore, new connections, messages, resources, and procedures are generated, making it extremely hard to evaluate this type of system.

There are similar patterns in how historically different emergency response organizations have reacted facing extreme events. This research illustrates and identifies those patterns as elements either to incorporate or analyze in a synthetic scenario. We argued that if the emergency response organization, in all the levels of reaction, has a clear incident management system, then it will be possible to identify vulnerabilities making use of mathematical techniques and simulation paradigms.

This hybrid simulation methodology presents two techniques for analyzing the initial layout of an emergency response organization – social network and linear programming. This effort aims to identify areas in which both techniques can produce a synergy for evaluating the initial structure of the organization.

Since graph theory and structural statistical analysis have enabled the development of many social network techniques, based on sociograms and matrices, we will use those approaches for understanding, evaluating, and predicting the performance of an emergency response organization that performs its tasks in a networked decision making scenario.

Someone could ask: why do we not directly apply graph theory in a network centric environment? The answer is simple: in past decades, researchers from the field of psychology have conducted a vast number of experiments to model and to evaluate the relationships among social entities; we argue that an emergency response organization is a social entity in which teams, leaders, supporters, decision makers, devices, machines and so on, are all integrated for protecting society before and after an extreme event. Therefore, a hybrid simulation that incorporates a mathematical interpretation of the dynamic relationships of different objects in a networked scenario could enhance the current response systems and plans for disaster management.

Methodology for developing a NCDM analysis

The way we will conduct this study is similar to the hybrid methodology proposed and only different in the analysis of five recent extreme events made with the purpose of detecting the features most significant for modeling and testing the different simulation techniques. Figure 6 shows the steps considered, and they are explained below:

- Determine the organizational structure based on network centric concepts and contingency theory. Two critical documents provide a good portion of this information: the Incident Command System (ICS, 2005) and the Emergency Operation Plan (EOP). The use of databases (from command/control or training systems) could provide a more accurate structure of the nodes and their tasks.

- Using SNA technique and linear programming (LP), analyze the emergency organizational structure. The predictive outcomes should be shown to decision makers and stakeholders in order to infer the organizational behavior.
- Identify the critical events according to the EOP of the jurisdiction. Parameters should be entered according to the manner defined in this research.
- If data exists, conduct a structural analysis (multivariate analysis) in order to identify correlated data. This information could be obtained from databases, surveys, expert interviews, and organization in the loop.
- Identify the features most appropriate in DES, SD, and ABM for modeling the objects, attributes, and flows that represent the organizational structure under an extreme event.
- Test the interoperability of models, variables, and parameters among the three simulation techniques. Calibrate the model.
- Select a timeframe for capturing the matrix of relationships among the nodes; then apply network analysis for testing the evolution of the organization. Notice that so far, we are dealing with the simulation model, but the possibility is still open for applying network analysis to the organization in the loop or to a command and control system in real time.
- If data exists, statistical analysis should be made in order to compare synthetic data (obtained from simulation) and data obtained from the organization in the loop. Provide measures of validation of the model.
- If the model can be validated, then conduct a design of experiment (DOE) for optimizing either the structure or EOP of the organization.
- If the model can be validated, define metrics and testing for identifying vulnerabilities in the organizational structure.

- Use the model to support the AAR in real scenarios and training organization in the loop

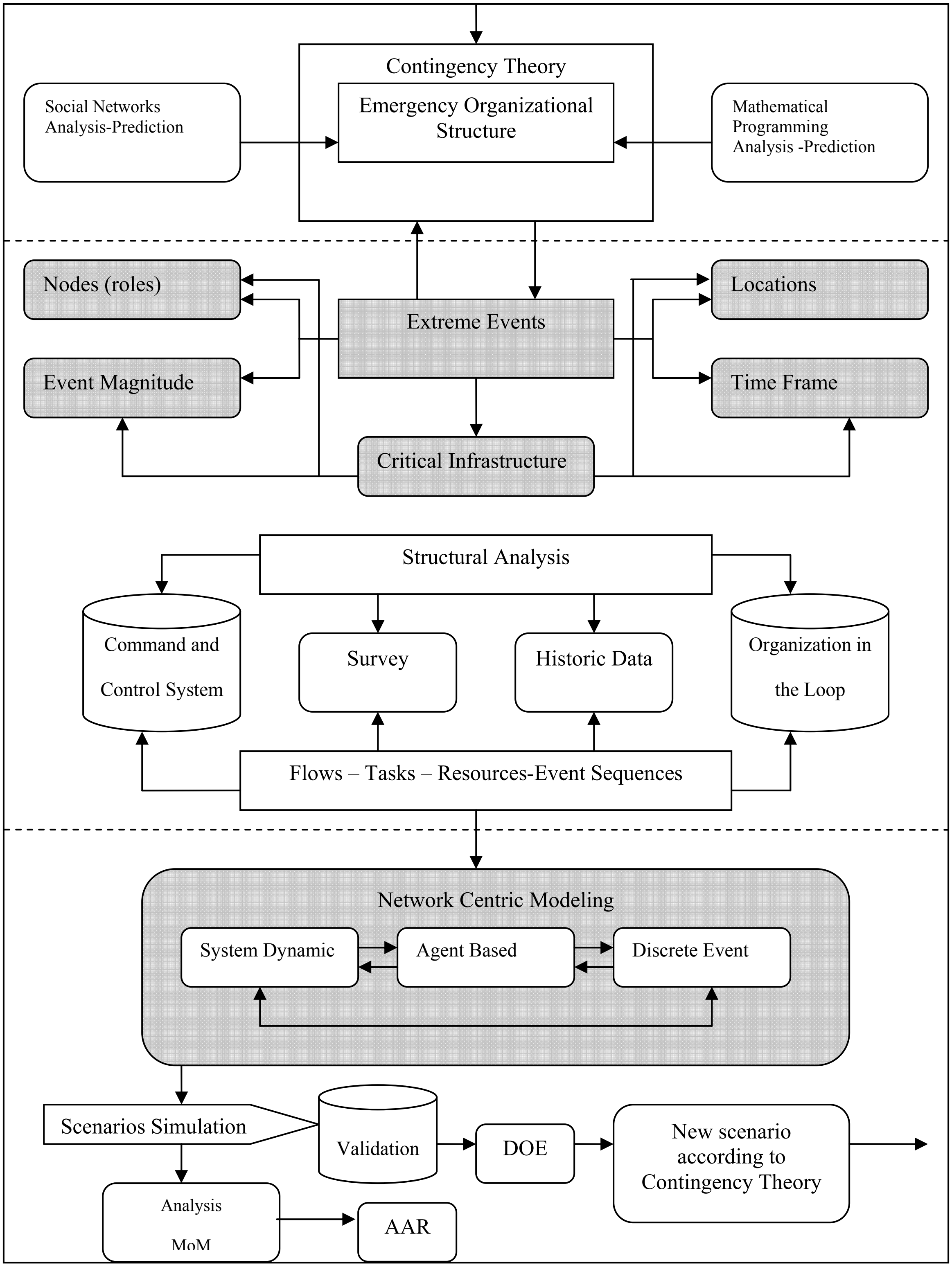


Figure 6: Methodology for implementing the hybrid simulation

Questions for testing in the simulated hybrid model

We define two types of questions for testing the hybrid simulation model.

Technical questions

- What features of an emergency response organization are possible to simulate in a networked scenario?
- Is there a more suitable simulation technique for modeling the interactions among nodes in an emergency management organization? (Testing best candidate simulation technique)
- How could two simulation techniques work together in a network centric scenario?
- How could a model enhance its usefulness when combined with graph theory?
- What mechanism of control could a modeler use for controlling a hybrid simulation?
- Is it possible to combine team performance with flows and tasks carried out by nodes in an emergency organization structure?
- Can the hybrid simulation be validated for predicting performance of an emergency organizational structure?

Operational questions

- What social network metrics are more significant for designing an organizational structure?
- Does the *network diameter* increase or decrease in an organizational structure when it faces an extreme event?

- How could the position and performance of a node in the network determine the behavior of the whole organization?
- How could the agent technique improve the validation of a NCDM scenario?
- Is the hybrid model simple enough to be used for decision makers and stakeholders to improve their ICS and EOP?
- Could the hybrid model be suitable for supporting the AAR of a real disaster independently of its size and location?
- Does the hybrid model improve organizational learning and lesson learned concepts?

Assumption for modeling scenarios (types of events)

We make a new categorization of extreme events based on the necessity for quantifying the concept of an extreme event. Some of the properties and implications defined by Sarewitz and Pielke (2000) are utilized in the elaborated categorization.

In the context of this dissertation, "scenarios" are defined as the combination of events, organizational deployments, tasks, resources, and policies for facing extreme events. These four characteristics allow visualization of a preliminary layout for modeling a NCDM environment. At the same time, the scenario definition provides a framework for developing a mathematical approach to the interrelationships produced among all the nodes which make up an emergency organization.

We define an extreme event in an organizational context: "Extreme event is an *n* dimensional vector which has two attributes named magnitude and direction. The dimension *n* is a function of the number of nodes which turn out to be affected, the event consequence is represented by the vector magnitude and the area affected is represented by the vector direction."

According to this definition, in an organization with *n* nodes, we are able to identify three types of events: The first affects only one set of nodes and is known as an isolated event (IE); the second one affects *n - k* nodes (*1< k <n*) and is known as a partial event (PE), and the third one affects the whole organization (many jurisdictions) and is known as a universal event (UE). Figure 7 shows an extreme event affecting an organizational emergency structure.

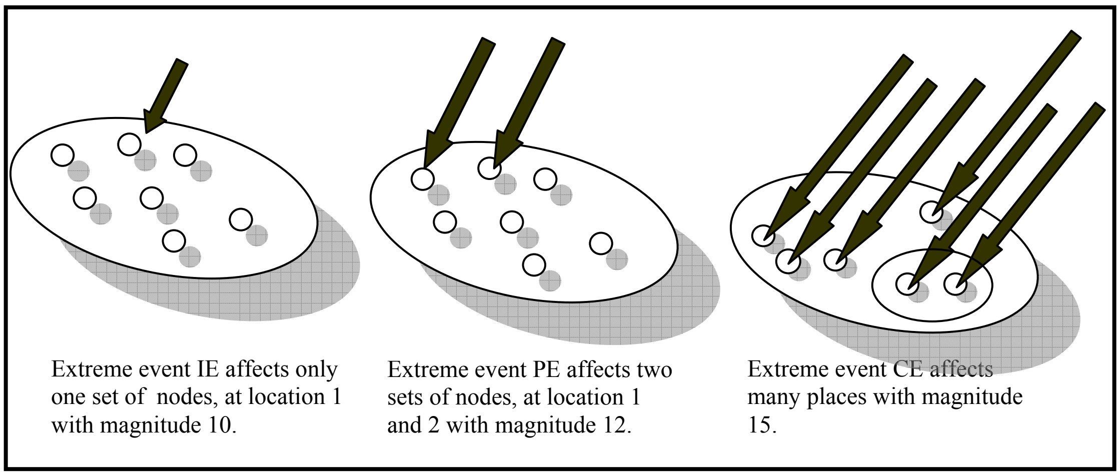


Figure 7: Classification for modeling extreme events

For instance, we can characterize one event as PE [3, 12, 5, 4], which means that this is a partial extreme event affecting 3 sets of nodes with magnitude 5, at 12 locations and it hits the locations at time 4. Note that the characterization will enable the measurement of performance in the organizational structure as a whole, since the type of event and its associated attributes will produce different reactions in the complete emergency structure, according to the fixed procedures previously designed by the organization.

A contrast between the classification formulated by Sarewitz and Pielke (2000) and the classification formulated in this research is shown in Table 13. We estimate that the vector representation allows preserving four properties from Table 3.

Table 13: Contrast between Sarewitz and Pielke (2000) extreme event properties and those proposed in this research

<table>
<tr><th>Properties</th><th>Implications for decision making</th><td rowspan="5">X_1 = Number of nodes

X_2 = Event magnitude

X_3 =Number of locations affected

X_4 =Event time

Vector for modeling different events.</td></tr>
<tr><td>Rare</td><td>Little opportunity for learning.
Relevant experience may be lacking.
Rare events may control system evolution.</td></tr>
<tr><td>High consequence</td><td>Attention will be focused on the event.
Decisions matter.</td></tr>
<tr><td>Time pressure</td><td>Limited time for analysis.
Stress producing.</td></tr>
<tr><td>Affects large numbers of people and/or large ecosystems.</td><td>Group decision, leadership, government action, trust, and cooperation/communication among stakeholders are important for the implementation of effective decisions.</td></tr>
</table>

<u>Main characteristics of an organization facing extreme event scenario</u>

In order to identify the main characteristics that an organization depicts facing extreme events, we analyzed five cases in which natural and man made disasters have produced a huge impact in the population. Our attempt was to identify the most significant variables, nodes, flows resources, chains of command, sequences, signals, and others quantitative factors required for modeling the behavior of an emergency response organization. These are the events analyzed:

- Chernobyl Nuclear Disaster, 1986, Ukraine (Appendix A)
- Oklahoma City Bombing, 1995, USA (Appendix A)
- Kobe Earthquake, 1995, Japan (Appendix A)
- Hurricane Mitch, 1998, Central America (Appendix A)
- Hurricane Katrina 2005, USA (Appendix A)

The five cases analyzed have in common that all of them could have had defined emergency procedures based upon information technology. Nevertheless, according to our research, only Hurricane Katrina encompasses all the characteristics required to be characterized as a NCDM scenario mainly because there are organizational and machine behaviors collected in the database of the C2 systems.

The findings found in each event are presented in Appendix A with the structure shown in Table 14.

Table 14: Attributes used for analyzing the five cases of extreme events

Extreme event	Define scenario
Features for modeling	Information flow and resources flow. Disaster planning. Communication system. Situation awareness. Interoperability. Human Factors. Chain of command.
Classification for modeling	According to size, level, and consequences.
Lesson learned	Hints at direction for the simulation and after action review.

After analyzing the most significant factors in the deployment of an emergency response organization, we built Table 15 based on nine factors. Conclusions regarding the features useful for modeling and selecting the most suitable simulation technique are presented at the end of this chapter.

Table 15: Comparing extreme events

Factors	Oklahoma Bombing 1995	Kobe Earthquake 1995	Mitch Hurricane 1998	Chernobyl Nuclear Disaster 1986	Katrina Hurricane 2005
Extreme event	Isolated event: Bombing	Earthquake followed by fires in urban areas. **Disruption of public infrastructure**	Hurricane followed by floods and **disruption of public infrastructure**	Isolated event: Reactor explosion Extreme consequences at the time	Hurricane followed by floods and looting, **disruption of public infrastructure**
Area affected	Small area into Oklahoma City. Perimeter was rapidly delimited.	Three main Japanese cities. Largest area but very well delimited.	Largest area affected by three days, three countries suffered the consequences simultaneously	Initially a small area which evolved toward a continuous event that involved several countries.	Extense and dynamic area; there was an evolution of the magnitude of the event at the time.
Actors	Scalable participation of nodes. Local reaction was clearly significant.	Many nodes were involved for several days. **No well defined jurisdiction,** unclear chain of command, confused response plan. Not all the resources available were used.	Many organizations without any coordination. Lack of unity of control. Lack of command. **No well defined jurisdiction.**	Scalable participation, from the local to national authorities. Required specialized commander in the incident zone.	Nodes from Federal, State and Local level were involved gradually. Local authorities played the main role. **Delimited jurisdiction.**

Factors	Oklahoma Bombing 1995	Kobe Earthquake 1995	Mitch Hurricane 1998	Chernobyl Nuclear Disaster 1986	Katrina Hurricane 2005
Data base available	Only semantic documentation. **No quantification of sequences.**	Only generic reports or focusing over a factor. **No quantification of sequences.**	Only semantic documentation. **No quantification of sequences.**	Lots of research from a technical perspective, no decision making analysis. **Sequence defined by the evolution of the event.**	Yes, not public domain. Federal government reported a quantitative analysis. **Clear sequences of the reaction of different levels, clear delays in some authorities.**
Decision Making Process	Clear. **Flows could be identified and modeled making use of surveys.**	Poor, difficult to model chain of command.	**Unclear, it is difficult to identify chain of command.**	Confusing and there is only generic information. Technical data available but this does not have relationship with decision making process.	The best extreme event suited from the perspective of decision making process. **Good chance for modeling if all data were available in the database of the command and control systems**.

Factors	Oklahoma Bombing 1995	Kobe Earthquake 1995	Mitch Hurricane 1998	Chernobyl Nuclear Disaster 1986	Katrina Hurricane 2005
Readiness	No, mainly by the absence of previous attacks. **No documented training before the attack, or any simulation model studied before of the attack.**	Yes, for the previous experience of Japan in Earth-quakes. **Documented training at the local level. No simulation model known for studying organizational response.**	No, civilian and military authorities were unprepared for an event of that magnitude. **No training before the event, no simulation model for analyzing a best response.**	No, reactions were assumed according to the evolution of the event. **Training was made at level of technical people who managed the plant, no organizational training, no simulation model known for studying organizational response.**	Yes, based on National Incident Management System. (NIMS) **No training known for facing Hurricane, but previous events provided the best lessons for diminishing the consequences. No simulation model regarding to NIMS is known so far.**
Communication systems	Yes, event affected small portion of telephone system, but demand collapsed the system. Problem with **interoperability** of radios in local authorities.	Unclear and only based on physical communication.	Lack of i**nteroperability** prevented communications among different groups and agencies.	No information available.	Initially very well defined.
Command and Control	Yes.	Based on Local authorities, but lack of unified command. **National government did not realize the magnitude of the event.**	No sustained Command and Control.	Confusion in the first three days. **National government did not realize the magnitude of the event.**	Confusion. **National government did not realize the magnitude of the event.**

Factors	Oklahoma Bombing 1995	Kobe Earthquake 1995	Mitch Hurricane 1998	Chernobyl Nuclear Disaster 1986	Katrina Hurricane 2005
Situation Awareness	Very well defined likely by the characteristic of local event. **It assumed a useful use of remote sensors like satellite images and GPS.**	Poor, **local authorities did not transfer their assessments to other levels and horizontal** agencies. **It is assumed deficient use of sensors available since they were not used on time.**	Event magnitude did not permit assessment of the situation mainly because the agencies in charge of this activity also were affected by the event. **No known use of sensors.**	Unclear, the worst situation awareness in the five events analyzed. The magnitude of the event only was known days after the explosion.	The magnitude of the event did not allow **situation awareness as defined by the National Response Plan (NRP) and Incident Command System (ICS).**

We formulated four conclusions useful for implementing a conceptual design of a network centric scenario.

Conclusion 1: Organizational behavior and interactions among the nodes

We concluded that there exist three types of behavior in a network centric scenario: *causal, discrete, and internal behavior.*

Causal behavior triggers the sequence of reaction in an organization, this coming from either a natural or man made origin. In the context of extreme events, causal behavior can be represented as a continuous or discrete variable. Notice that we are not interested in modeling the physics, chemical or atmospheric characteristics of the event; our primary concern is to model the signals emitted by the event which fires the organizational reaction.

Those signals have different interpretations, and should be defined in the plans and management systems of an organization. Thus a type of signal could fire the reaction of a single local level, and consecutive signals could point out that it is necessary to involve multiple jurisdictions. *Causal behavior* is a candidate to be modeled as continuous or discrete signals in a NCDM scenario.

*Discrete behavior*s are the pair-wise interactions between the nodes of an organization. Usually the incident reports, textual research, and technical analysis refer to the *discrete behavior* as flows. Nevertheless, in order to model different transactions in the network, the modeler will need to distinguish between types of flows. For instance, the primary concern in a disaster is to keep the communication systems working, and the interactions produced through those communication systems should be modeled as discrete entities. SD technique identifies those flows as information and resources. We take those expressions, but since our model is more rich in detail, we differentiate among different type of information and resources.
Internal behavior is shown by the teams, task forces, agencies, commander's staff, etc; it is the most difficult part for modeling and validating and involves the decision making process, we will suggest a internal discrete behavior based on discrete entities.

<u>Conclusion 2: Data available for modeling the NCDM scenario</u>

According to the five cases summarized for purposing the model, we defined three types of data: "*semantic data,*" "*qualitative data*" and "*quantitative data.*"

Qualitative data is included in reports, public reviews, researches findings, and media reports. Qualitative data refers only to the event and its context. Always it describes the consequences of the extreme event as a function of the population affected and the public and private infrastructure damaged. The main actors are clearly identified. Most of the time qualitative data contain fuzzy numerical data as an attribute of a determined situation.

Semantic data is included in technical reports, after action reviews, plans to manage incidents, and format messages used in the command and control system of the organization. The National Incident Management System (NIMS, 2004) and Incident Command System (ICS) in the USA are classic examples of semantic data.

Quantitative data is numerical data used in a specific context, and it describes a process by mean of quantities, timing, and sequences. This data can be obtained only from two sources: either databases of the command and control systems that the organization used for dealing with the emergency or a very well defined survey made in the after action review of the event that includes all the critical actors in the event.

Semantic and *quantitative* data for modeling and simulating the deployment and posterior evolution of an organization will depend on the command and control systems that the organization had before, during, and after the extreme event, and the plans and incident command systems that the organization implemented before the extreme event.

For instance Hurricane Katrina is the event with the most data available for modeling the behavior of the complete deployment that the incident command system did at the local, state, and federal level. The reason is because there was a standardized management system used in all the levels and a command and control system which supported the collection of digital data for subsequent analysis. No other extreme event in the history of the extreme events has recorded the data required for modeling what happened, how it happened, and how the incident systems can be improved in the future.

In conclusion, data available for modeling a NCDM exists only in the database of the command and control systems of the organization; complementary data could be obtained from surveys and after action reviews collected from real people who were involved in the real extreme events.

Conclusion 3: Time scale and space scale in a NCDM scenario

The mapping between a simulated environment and the timing collected from the real events does not permit simulating time scale and space. The granularity of a network requires that each critical object, named "node," depicts its behavior simultaneously with other nodes. Thus the synchronization of the procedures only could be made if we consider one scale of time.

The space scale is not considered in this methodology, since our effort aims to understand the topological interactions among the nodes independently of their geographic location.

Conclusion 4: Main problems performed by an incident command system

- In general there is no assessing of the information to identify which were the priorities in the process of decision making.
- Sequences of events are not very well documented with the exception of Katrina.
- Fuzzy procedures among the nodes yield information overload and delay for the decision makers.
- Decision makers in the chain of command have a clear vision of the problem in their jurisdiction but do not have the complete situation awareness if the extreme event hits more than one jurisdictional zone. A higher position increases the decision maker's situation awareness, but it requires time to build.

- A lack of a standardized international structure to implement an incident command system was identified.
- After action reports make fuzzy identifications of actors, resources, capacities, and missions performed during the extreme event.
- There is no analysis between the correlation of extreme events and team performance.
- There are no models for simulating the chain of command.
- There are no distribution probabilities associated to processes, sequences, and flows.
- After action reports do not show any methodology for increasing situation awareness.
- Most extreme events report lack of “unity of command” to ensure unity of effort under one responsible commander for every objective.
- The integration of human beings and machines such as radar or an alert warning is not reported or its analysis is scarce in quantitative term.
- After action reports do not include any measure of performance in the organization.

CHAPTER FOUR: MODELING DOMAINS AND APPLYING METRICS INTO AN EMERGENCY MANAGEMENT ORGANIZATION

Network centric decision making under extreme events: Conceptual domain

Ahvenainen (2003) described the relationships that take place in a network centric warfare scenario based on three domains: *physical, information,* and *cognitive*. These domains will be used in the context of this research to model the observable relationships when an organization deals with extreme events.

- Physical domain: This includes the critical infrastructure which has a strong impact in the network centric processes. The main problem in this domain is the infrastructure interdependencies among the critical systems, as only one contingency event may affect the whole interconnected infrastructure of one or several locations. Therefore, this methodology provides a framework for incorporating this domain mainly as a continuous simulation, with feedback loops which may represent with more accuracy the interdependency among critical infrastructure. Since many of the systems are dependent upon electric power generation, we will include this topic in our test bed, leaving open the option for integrating more refined models with another critical infrastructure using the same technique. As a result, we will attempt to demonstrate how either continuous or discrete flows of the interconnected infrastructure, could alter the behavior of an emergency management organization.
- Information domain: This domain provides the capability to detect, process, and share information among human beings and machines in the network. According to the five

cases analyzed previously, we will model *information* domain as discrete processes in where there exists an influence of the *physical* and *cognitive* domain. Two techniques were selected for modeling this domain; discrete event simulation and state of transition techniques.

- Cognitive domain: We modified the original Ahvenainen concept of the *cognitive domain* because our prime goal is to develop a framework for studying the network centric processes carried out in an organization composed mainly of teams and task forces. We will concentrate our research on providing a mechanism to model how an extreme event could disrupt the procedures and tasks that a group of persons must carry out in an extreme event.

Making use of the Yerkes-Dodson curve, we will depict the curvilinear between stress and performance (Yerkes & Dodson, 1908), and based on a System Dynamics technique we will incorporate the effects of the Yerkes-Dodson curve in an overall model (Rudolph, et al. 2002). Nevertheless, the methodology will still be open for incorporating other models either for team performance or cognitive decision makers' processes.

Figure 8 presents the interaction between each domain and the best candidate simulation tools to be tested in a hybrid simulation methodology.

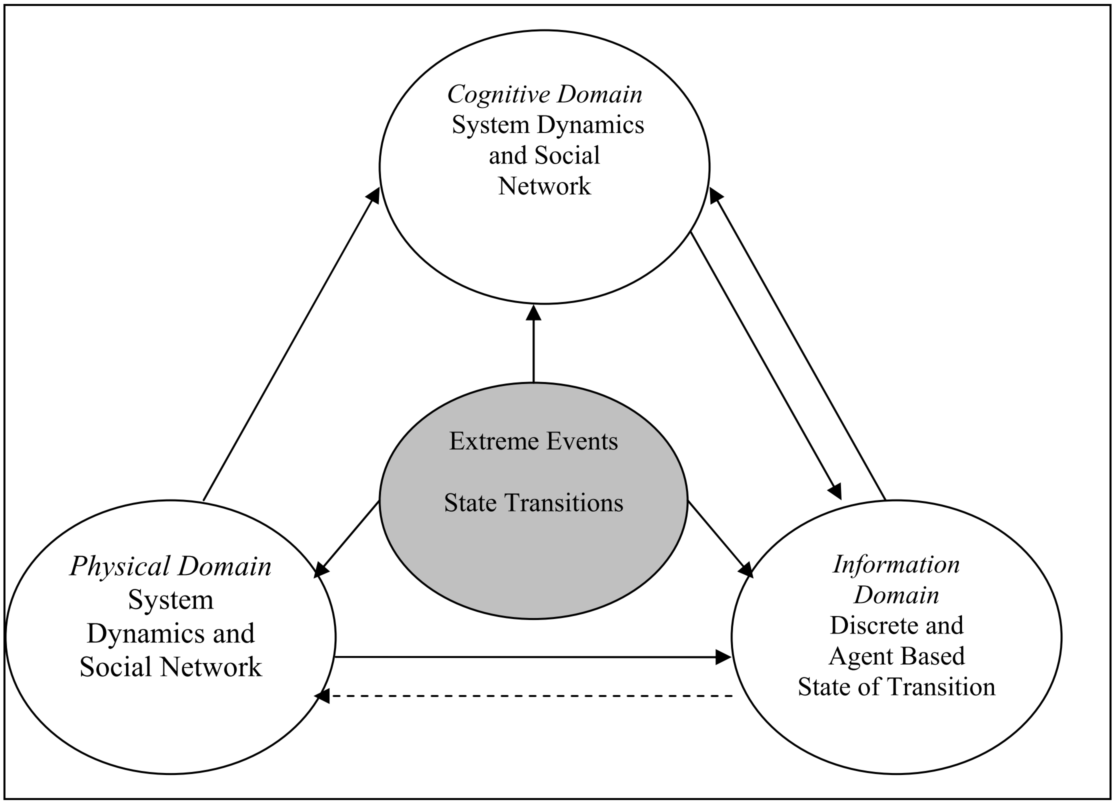


Figure 8: Simulation techniques by domains

In order to model the main scenario's interactions, we will use the three main simulation paradigms and the technique of social networks, which supports its analysis in graph theory.

After comparing the manuals, plans, and disaster procedures used for three countries (USA, Chile, and Honduras) and the reviews made by the United Nations, we concluded that there does not exist any *standardized international design* for dealing with the organizational structure, terminology, incident procedures, and interoperability in the management of extreme events.

Because of the lack of standards in this field, we will make use of terminology, structure, and procedures accessible in the National Incident Management System (NIMS, 2004) which coordinates federal, state, and local organizations to manage domestic incidents.

We suggest the hybrid simulation methodology based on the following assumptions:

- In a network centric scenario, the agents, processes, and alarms must be previously documented in an EOP, and historic data of the interactions of the emergency management organization should be available for performing a structural analysis.
- The network centric scenario can only be modeled if there exists a comprehensible structure of relationships, procedures, and hierarchies between the levels of decision making.
- The agents depict a discrete behavior and they transfer messages and resources in the network according to the extreme event evolution.
- The agents make contact with other agents using the allowed channels previously established in the plans and EOP.
- Agents' behaviors are highly dependent of the position that they have in the emergency management organization and of the type of extreme event that affects their jurisdiction.
- The network centric processes include interactions between human beings, remote sensors, and "intelligent" machines.

These assumptions are an effort to capture the main quantitative interactions of an emergency management organization which performs its tasks in a network centric environment modeled mainly as discrete and continuous flows.

In this chapter, we propose to study the changes in the topology of the organization by mean of graph's index and by testing hypotheses based upon Monte Carlo simulations of random and scale free networks. Throughout the methodology, we will combine an object oriented modeling approach with graph analysis, allowing investigation of complex emergency management organizations, especially when data is available. Because of the strong relationship between social network theory and graph theory, we will use both theories as similar terms for referring to the network centric processes.

Components of a network centric scenario and levels of aggregation

The level of fidelity of a simulated system is strongly dependent on the granularity that the modeler can incorporate in the model. While a high level of decomposition can imply an ability to simulate complex behaviors and their interactions, a low level of granularity could be easier for simulating, but likely less inference could be made from its outcomes.

Our approach enables us to make a mapping *one to one* between the real agents in an emergency management organization and the simulated entities in the model. This supports the hypothesis that if data is available, then it is possible to replicate some portion of how the agents perform their tasks when an extreme event affects their jurisdiction.

The benefits derived from a granularity *one-to-one* are multiple. For instance, it avoids dealing with several aggregation levels in the simulation, allows a direct mapping between real data and simulated data, and allows analysis of the significance of an individual agent in the organization.

Thus, we propose a methodology that distinguishes between the measures of performance for the agents' properties and measures of performance for the entire emergency management organization.

A high level of granularity and fidelity require that the organization be modeled as a set of agents. In the context of this research, we will use the term *nodes* for referring to the agents which are components of an emergency management organization. A *node* depicts toward its surrounding environment a *discrete behavior* which must be validated with historical data. The relationships between the *nodes* generate a network which represents the organizational interactions for responding to extreme events. We will refer to those relationships as *flows.* The overall network behavior arises from the isomorphism flows yield between two *nodes*, which are named *dyad flows.*

The *nodes* are critical objects, which could carry out the following tasks:

- Receiving data and resources and transferring those to others *nodes*.
- Receiving, processing, and transferring the data and resources to others *nodes*.
- Producing data derived of their perception of the environment and transferring it to others *nodes*.

In time, some nodes modify their relationships with other nodes, according to the dynamics changes in the network centric environment. The set of changes through time is called *longitudinal network.*

The flows carry pieces of data which we call *messages*. Using the SD terminology, we say that the flows can transfer either *information* or *resources.* The *messages* can have attributes according to the node sender.

To test the hybrid simulation methodology, we define six types of primitive nodal classes, each one with different internal objects and parameters. This approach enables us to replicate hundreds of *nodes* performing their interactions over the network based on six types of behaviors. In fact, we are providing a methodology for testing the mathematical structure of a graph merged with object oriented simulation technique, and thus take advantages of the synergy of both techniques.

Table 16 shows the nodes classification and their attributes; this categorization is a simplification based on the literature review and the current emergency management systems. Nevertheless the methodology remains open for incorporating new type of nodes.

Table 16: Types of nodes modeled in the test bed

Classes	Who (examples)	Attributes
1.Decision Makers	Chief of Federal Government. State Governor Mayor Commander Incident Chief of Local Police	Command according to the rules of incident command system. At the lower level has a shorter chain of command. Have available resources. Require information to make decisions. Span of control no more than five nodes
2. Staff-Planning	Operational Officer Logistics Officer. Intelligence Officer. Agencies Departments	Present a high skill in their field. Require data for supporting the decision Maker. Close contact with the decision maker. Their opinions can be non conclusive. Propose alternatives to the decision maker. Coordinate with other decision makers.
3.Situation Awareness	Analysis Group Map Situation Data Base	Provide contingency and timely information to other classes. In charge of keeping the *big picture*.
4. Support	People in charge of logistics resources. Chief of facilities. Hospital Director.	Public and private entities which have resources available for supporting the tasks decided by the decision maker.
5.Task Forces	Police, Fire Fighter, National Guard, Ambulances.	Work on the ground. Usually have double dependency from incident commander and their own authorities.
6.Sensors	Satellites, Radar, Warning Alert System.	Send signal according to defined rules. Sometime provide the first warning alarm. Supporting to situation awareness nodes.

The aggregation level enables *n nodes* which are instances of the six classes previously defined. The incorporation of individual *node* parameters permits us to distinguish among the different object behaviors. The attributes showed in the six classes allow allocating to the *node* (class) in the network structure.

Sequence for evaluating the networked centric structure

Figure 9 shows a holistic approach of the steps considered for evaluating the structure and performance of the emergency management organization. The process begins with the identification of *nodes*, *sequences,* and *procedures*. In absence of data, the best sources for capturing the organizational structure are the manuals, emergency operation plans, and incident systems. That documentation contains the standardized mechanisms cross-jurisdictional, statewide, and interstate "for coordinating response and obtaining assistance during a large-scale or complex incident" (NIMS, 2004).

Once the *nodes* and their relationships are identified, an analyst could apply social network analysis to study the position of the nodes in the network and to examine the characteristic of the whole network. This step can be enhanced with LP analysis.

The previous analysis corresponds to a static study of the emergency management organization, and here there are no dynamic interactions among the *nodes*, but based upon these results, either the decision makers or stakeholders could formulate hypotheses regarding the organization's future performance.

The alerting sequence of the local, state and federal emergency organizations is a function of the event magnitude. The event or set of events should permit for testing the synthetic reaction of the chain of command according to the EOP that each authority has generated for facing the most probably critical situations.

A significant subject in this methodology is how to simulate the internal nodes' behavior, since there exists only scarce data of the interactions in an emergency management organization, and the modeling of decision making processes have not been adequately explored, modeled, and validated in the simulation community.

Therefore, we make some abstractions of the internal structure of the nodes' behavior, and modeling those as a function of different messages that arrive and depart from a node according to defined internal rules. If data is available, we propose an intermediate approach for modeling the internal node structure based upon distribution probabilities.

The methodology proposes a way for selecting the flows of information and resources more relevant to the emergency management organization; nevertheless this topic should be tested with real data.

Once the events are detected, then we define a time frame for capturing a new set of relationships among the *nodes*. The process is iterative and could continue according to fixed times.

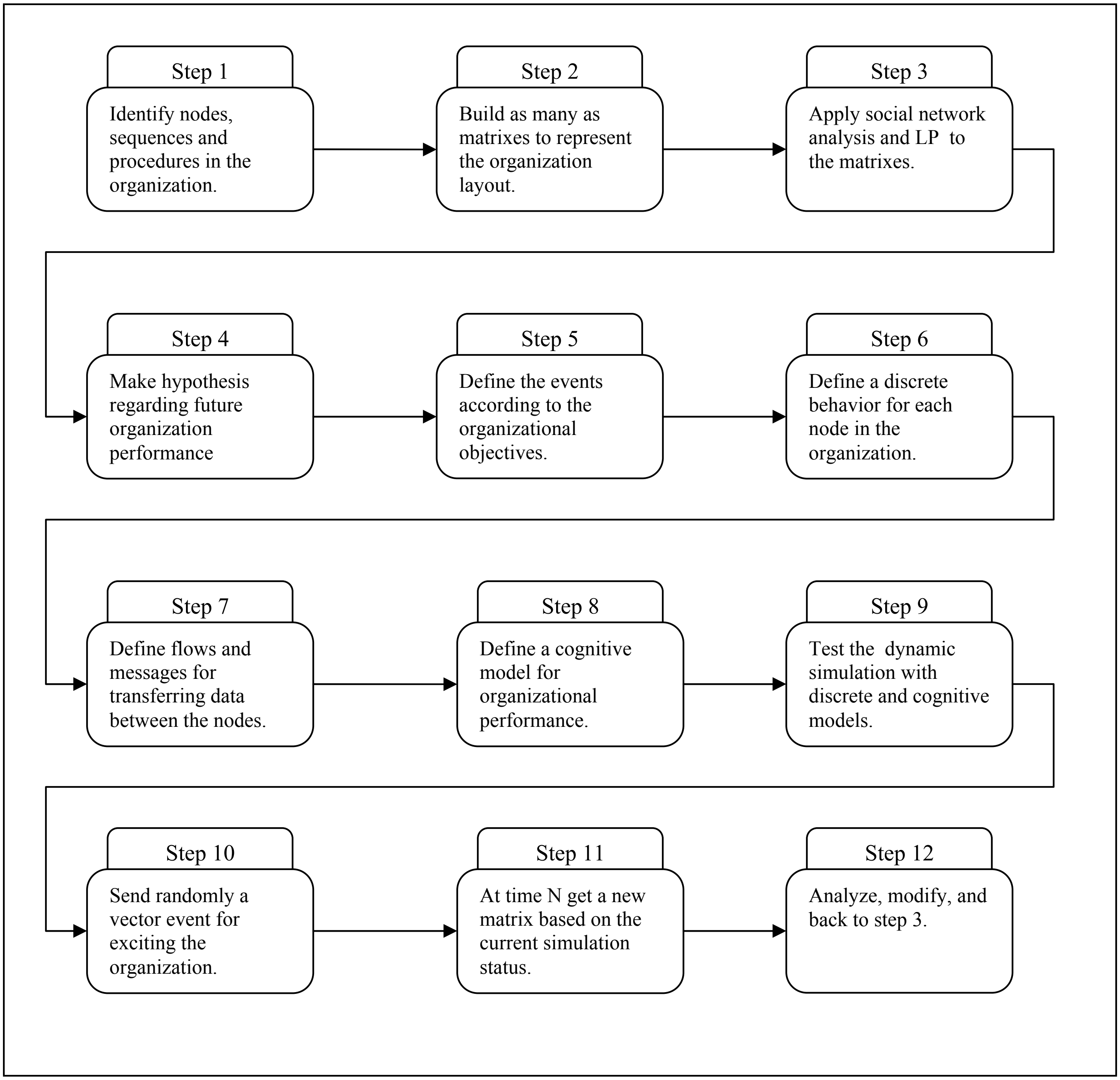


Figure 9: Steps for modeling an emergency management organization

Applying graph theory to the network centric decision making

We describe an emergency management organization by using graph theory, a *graph* G = (N, L) is defined by a *node* set $N = (n_1, n_2 \dots n_n)$ and an edge set $L = (l_1, l_2, \dots l_L)$, elements of the Cartesian product $N \times N = \{ (n,z) / n \in N, z \in N \}$. (Adaptation, Degenne & Forse, 1999; Wassermann & Faust, 1994).

The graph G presents n nodes and l_L edges; the total number of nodes in G is called the graph's order. The connections among the nodes are called arcs when the graph is directed and edges when the connections are undirected. In a directed and undirected graph the number of arcs or edges converging to the node n_i is named *in-degree* and the number of outbound arcs or edges is named *out-degree*. The sum of both indexes is called *node degree.*

Sometimes we need to use a graph as a set of edges and arcs; in this case:

> A graph is an ordered triple $G = (N, L, D)$ where the set N is the node set of the graph G; L is the set of edges, and D is the set of arcs of G. Notice the difference between the set L which stands for an undirected set of edges and the set D which stands for a directed set of arcs. If the set D =∅, the Graph G is undirected, and if the set L =∅, the Graph G is directed (Doreian, Batagelj & Ferligoj, 2005).

Most of the time, the nodes' relationships in a hierarchized organization are directed arcs, especially when a contingency plan points out that the procedures, notifications, and alarms must follow a determined path among the *nodes*; in this case each element $l_i \in L$ must have a direction. A directed graph is also known as a *digraph.*

A *node* is defined as an object which plays a role in the emergency management organization; that role is designated according to Table 16. In order to define the protocols of relationships, affiliations, and attributes of the different *nodes*, we consider three types of variables by each set of nodes (Netminer, 2005):

- *Adjacency variables*: Describing a set of relationships among the *nodes* using directed graphs and weights. We could find more than one adjacency variables in an emergency management organization. Each adjacency variable is a layer, and we could analyze simultaneously several layers of organizational interactions.
- *Affiliation variables*: Describing the clusters of relationships produced between subsets of *nodes*. The affiliation variables can be analyzed by using three main methods: co-membership, overlap, and bipartite matrixes. Affiliation variable enable us to analyze the behavior of nodes which participate simultaneously in different events. The simulation community has not given enough attention to this variable due to the difficulty in controlling object behavior performed simultaneously in different scenarios.
- *Attributes variables:* Describing the individual attributes of each *node*. The attributes incorporated have discrete values.

We classified and described the network's characteristics and node's measures more suitable for this research. The starting point is the *mode* concept which explains how many sets of nodes are used in the network analysis. The most frequent social network studies consider *one-mode*, *two-mode* and *ego-centered* networks analysis.

A one-*mode* network analysis is the study made over the graph $G = (X, U)$ cited at the beginning of this chapter.

A *two-mode* network considers the analysis of the graph $N= (U1, U_2, R, w)$, where the first network is denoted by $U_1=\{ u_1,u_2,\ldots u_n\}$ and the second network is denoted by $U_2= \{v_1,v_2,\ldots v_n\}$ with $U_1 \cap U_2 =\emptyset$; the relation $R \subseteq U_1 \times U_2$ is the set of edges between the nodes in U_1 and nodes in U_2; the w represents the weight in the graph. (Doreian, Batagelj & Ferligoj, 2005). Researches have given little importance to *multi-modal* analysis with more than two modes; nevertheless this kind of network provides a rich structure for understanding the organization performance with multiples tasks in different scenarios. We will analyze in depth the *two-mode* network and will leave the methodology open for a higher modal analysis when there exists more tools and research on this topic.

An *ego-centered* network analysis makes a quantitative analysis of a focal node, named *ego,* and their adjacent nodes and connections. The *ego-network* of the node n_i contains all the sub-networks which are focusing on node n_i. The most significant tool for analyzing an *ego-network* configuration is the concept of triad, which will be explained in depth because it has significant statistical consequences for the analysis of the whole network.

A complementary approach considers two classifications: *individual networks parameters* and *global networks parameters.* Buskenks (2002) stated that in the context of information diffusion rates, some conjectures regarding the effects of individual and network parameters can be made to predict the performance of the network.

Since a network-centric structure is strongly related with a *one-mode* network, we will use this configuration as a major source of network analysis. Complementary, to gain insight on the organizational structure, we use *two-mode* analysis and *ego-centered* analysis. Nodes' features that are not derived from their structural location in the network are named attributes and they improve the analysis of *one-mode* network analysis. This research models a framework which could be adaptable to any organization, independently of the type of extreme event. According to the empirical evidence found in the five cases analyzed and although the local, state, and federal authorities play the main roles dealing with extreme events, we incorporate the nodes that represent nongovernmental organizations and private entities which also play a relevant role in an extreme event.

The processes of decision making in emergency structures are scalable and depend on the size and type of the extreme event. In order to identify the complexity that arises in the organizational interaction, we designed a test bed, based upon ICS (NIMS, 2004). Thirty-seven nodes were situated in an adjacency matrix, which represents an emergency organization (Appendix 2). The relationships, affiliations, and attributes of the organization were arbitrarily located according to conventional EOP. Figure 10 shows the digraph derived from the adjacency matrix.

The digraph shows the relationships between the components of an ICS and it includes the chain of command in the organization. In order to deal with complexity similar to that found in a real scenario, we incorporated a vector partition in the matrix to assign nodes to the federal, state, and local levels.

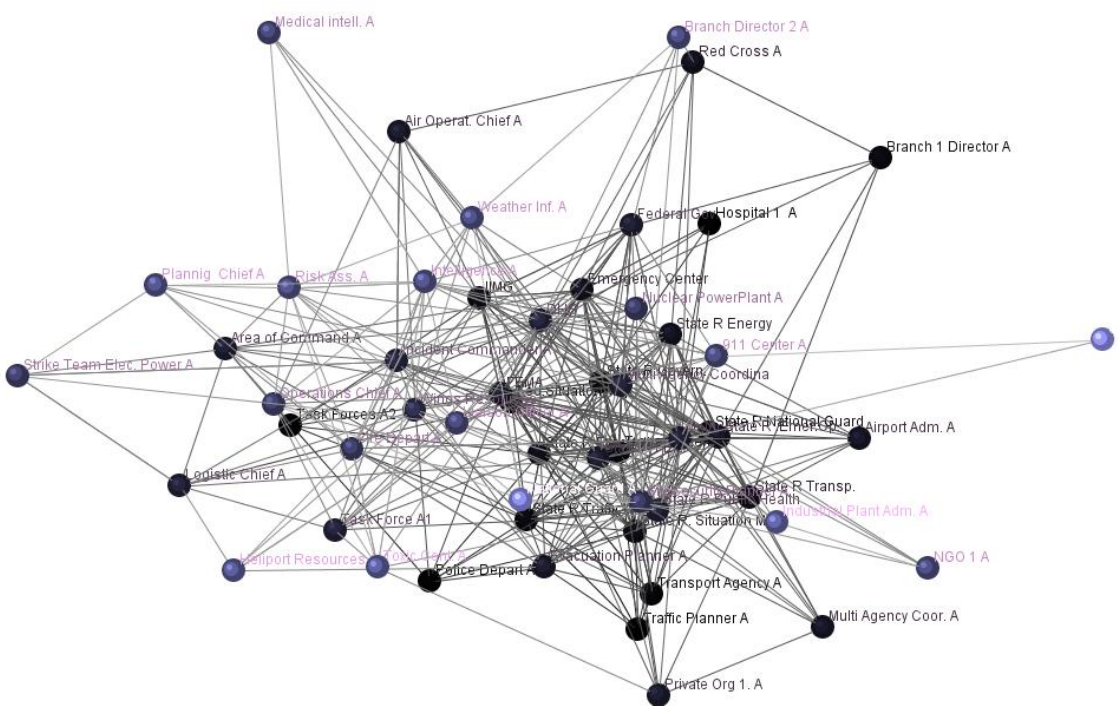


Figure 10: Adjacency matrix used in the test bed of an emergency organizational structure

To increase the association between graph theory and simulation techniques, we identify five types of nodes and one type of arc in the adjacency matrix which could be modeled in either a discrete or continuous model (see Table 17).

Table 17: Nodes classification in the adjacency matrix

Isolate nodes	Degree equal to 0
Transmitter nodes	In-degree is equal to 0, but Out-degree has a value.
Receiver nodes	In-degree has a value, but Out-degree is equal to 0.
Carrier nodes	The measures of In-degree and Out-degree are equal to one
Ordinary nodes	In-degree and Out-degree are greater than 1.
Bridge node	If it is removed, would disconnect the network

Networks and measures classification

In Figure 11 we suggest a network classification, a set of nodes' properties and arcs' features which can be used for testing a complex emergency management organization. The mathematical foundation of each property is explained in the context of an emergency organization, and we propose in advance some relationships of those properties with either a discrete event simulation or system dynamics model.

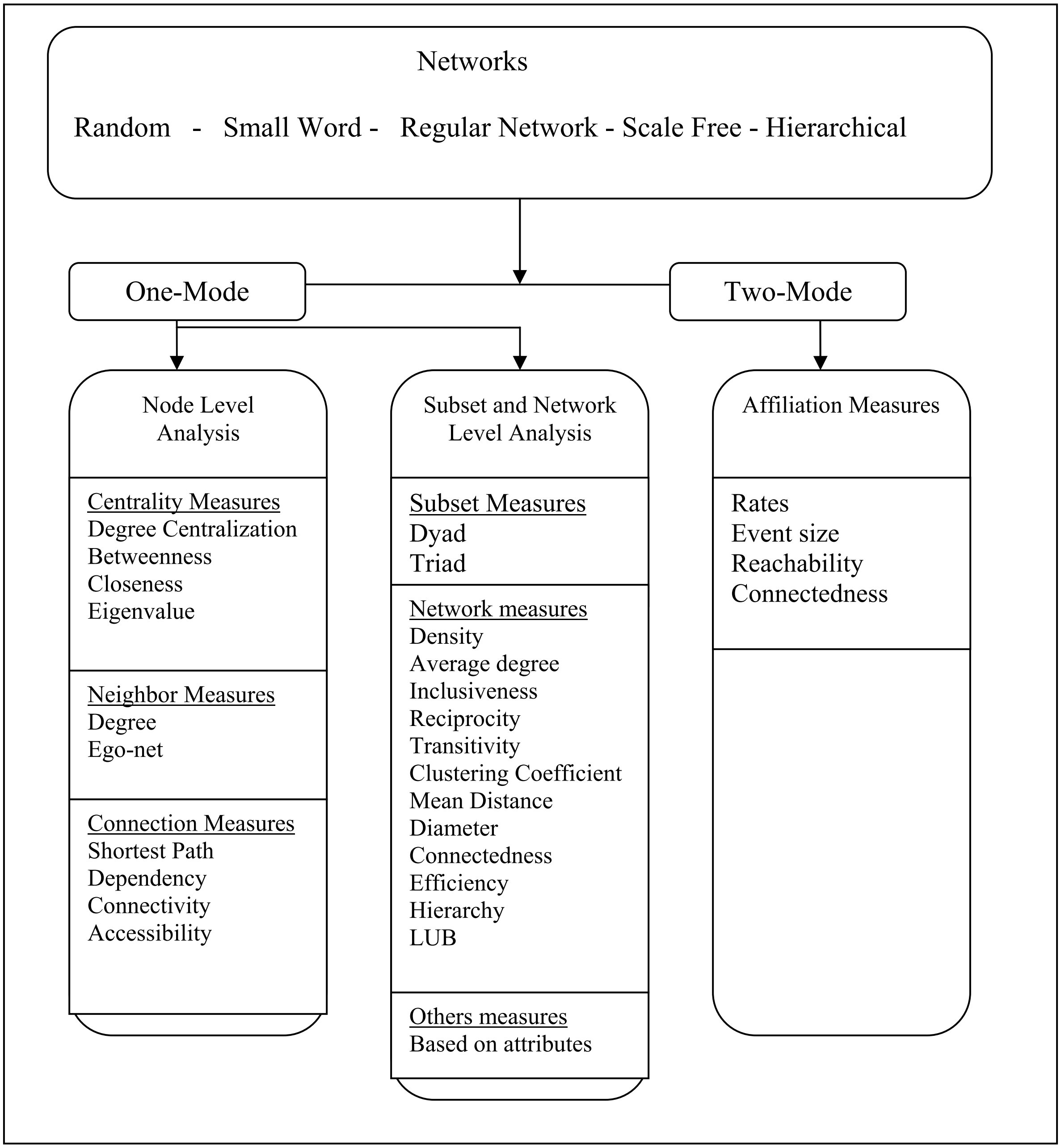


Figure 11: Classification of networks and nodes properties

- *Random Network (RN)****:*** Nodes are connected with others nodes according to a specific distribution. This type of network has particular properties such as a large variation between nodes' paths, low clustering, and random topology. Three main distributions are used for generating *RN* are uniform, normal, and Bernoulli, if the network has one of the named distributions then we state that they have a *scale.*
    - Over a network centric scenario, it is significant to understand the main implications of the *RN* behavior, since we may predict the performance of the organizational structure if it presents a similar configuration to that identified in a *RN*. Care (2005) proposed a minimum of fifty nodes in order to guarantee common properties in the digraph. The type of properties will depend on of the analysis carried out by the organization.
    - For instance a digraph with *n nodes,* generated from a uniform distribution implies that the probability of choices is $\frac{1}{2^{n(n-1)}}$. The idea behind this distribution is that each possible configuration of an adjacency matrix of n nodes which has a sample space of $2^{n(n-1)}$ different configurations has the same chance of occurring (Adapted from Wassermann et al, 1994).
- *Small World Network (SWN):* Network based on Milgram's experiment which showed that people in different locations are connected by a short chain of persons. This class of networks is very regular and has good clustering (Cares, 2006). According to Milgram in a *SWN,* the geodesic paths do not reach more than six steps (Milgram, 1967).
- *Scale Free Network (SFN):* Network with a *Power Law* distribution of the links among the nodes, where the probability that a node has exactly *k* links is $P(k) \approx k^{-b}$, where *b* is the

degree exponent. The *SFN* has a large amount of nodes with few connections, and a small number of nodes, known as hubs, exhibit a large number of connections.

- *Regular Network (REN):* Usually named as *Lattice networks*, *REN* have the same ratio of connections among the nodes as the random network, but the clustering coefficient is uniform, and therefore its structure is more regular.
- *Hierarchical Network (HN):* Formed by the structure of an organization, it shows the chain of command and the formal vertical and horizontal relationships among the nodes. According to our definition of *HN,* it could be classified as any of the four networks previously mentioned.

<u>One–mode network: Measures and implication for an emergency organization</u>

Centrality measures

- *Degree centrality*: Standardized measure that shows the proportion of nodes adjacent to the node n_i and the maximum value that could reach the n_i in the network. This index allows comparing different network size.

$$\text{Degree centrality} = \frac{d(n_i)}{n-1} \qquad d(n_i) \text{ is the number of nodes adjacent to } ni.$$

- *Degree centralization:* Measure of variation in the degrees of nodes divided by the maximum degree variation which is possible in a network of the same size. The index can be used to determine the degree of centralization of the whole network. The index reaches the maximum value 1 when one node n_i is connected with the n-1 other nodes, and the other nodes are connected only with n_i.

$$\text{Degree centralization} = \frac{\sum_{i=1}^{n}[C_D(n^*) - C_D(n_i)]}{[(n-1)(n-2)]}$$

The $C_D(n_i)$ are the n nodes degree indices, and $C_D(n^*)$ is the largest observed value (Wassermann & Faust, 1994).

- *Betweenness centrality*: Over an undirected network, the proportion of all short paths between pairs of nodes (*geodesic path*) in the network and the geodesics which go through the node n_i. In an organization, assuming that the information and resources go by a geodesic path, the nodes with a high betweenness score will be in central positions and will play a vital role in the flows of information and resources.

$$Betweenness-centrality(n_i) = C_B(n_i)/[(n-1)(n-2)/2]$$

Where $$C_B(n_i) = \sum_{j<k} n_{jk}(n_i)/n_{jk}$$

- *Betweenness centralization*: The variation in the betweenness centrality of vertices divided by the maximum variation in betweenness centrality scores possible in a network of the same size.

$$\text{Betweenness centralization} = \frac{2\sum_{i=1}^{n}[C_B(n^*) - C_B(n_i)]}{[(n-1)^2(n-2)]}$$

- *Closeness centrality:* Useful index to measure the closeness of a node n_i to the other nodes in the network. It is measured by the inverse of the sum of the distance from a node to all other nodes, which is normalized by multiplying it by *(n-1)*.

$$\text{Closeness}\,(ni) = \frac{n-1}{\sum_{j=1}^{n} d(ni, nj)}$$

For a directed network, each of *in-closeness centrality* and *out-closeness centrality* is measured separately, depending on whether the distances 'from' or 'to' other *nodes* are considered. The idea is that a node is central if it can quickly interact with all others.

- *Closeness centralization:* To measure group centralization using nodes closeness centralities. This measure enables us to know the variability of individual closeness centrality scores (Adapted from Netminer, 2005).

$$\text{Closeness centralization} = \frac{\sum_{i=1}^{n}[C'_D(n^*) - C'_D(n_i)]}{[(n-2)(n-1)]/(2n-3)}$$

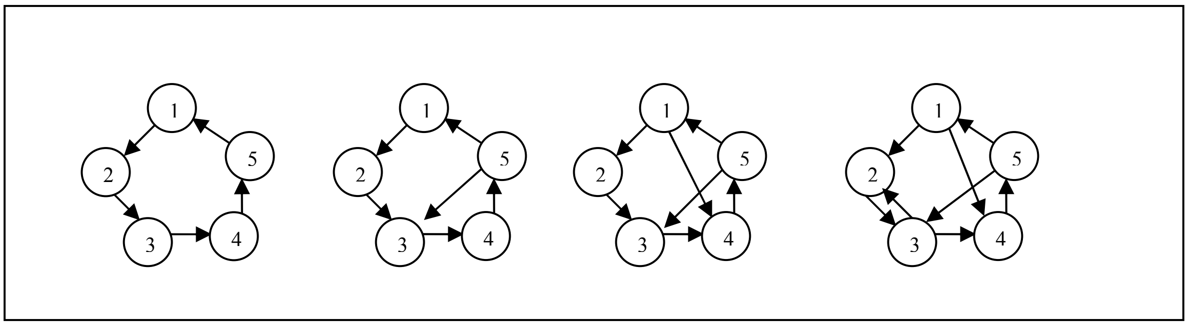
- *Eigenvalue (Perron-Frobenius theorem):* This measure guarantees that there exists an *eigenvalue* which is real and larger than or equal to all other *eigenvalues* in magnitude. The largest *eigenvalue* is often called the *Perron-Frobeniuos eigenvalue* of the matrix which is denoted by *λ1(C)* for a graph *C*. Further the theorem also states that there exists an *eigenvector* of *C* corresponding to *λ1(C),* all of whose components are real and non-negative (Jain & Sandeep, 2002). The *eigenvalue* allows us to find out the presence or absence of closed paths in a network structure according to the following proposition:

If in the network there is no *closed walk, then λ1(C) = 0*

If in the network there is at least a *closed walk, then λ1 (C) ≥ 1*

If in the network there is *a closed walk and all closed walks only occur in sub-graphs that are cycles, then λ1 (C) = 1*

Figure 12 shows four *sub-graphs* with different topology (Adapted from Care, 2005)



λ =1.00	λ=1.19	λ=1.36	λ=1.52

Figure 12: Measuring networked effects by using eigenvalues

Neighbor Measures: Set of indexes to evaluate adjacent nodes in a network

- *Degree:* Measure to identify the size of the direct connection between the *ni* node and its vicinity. The number of flows that are incidents over one node is known as *in-degree* measures and the number of flows that a node sends to other nodes is named as *out-degree*. Both measures allow identifying the type of node and the vulnerability of the distributed decision making.
- *Structural hole*: Show six indicators to evaluate the position of all nodes in the network: redundancy, efficiency, effective, size, constraint, and hierarchy measures. These

measures show the separation between non-redundant contacts. Two criteria rule the creation of a structural hole: cohesion and equivalence.

- *Ego-network:* Measure to analyze the local connection structure by each node; this index calculates the size and density of a selected focal node.

Connection measures in a network

- *Geodesic distance:* Index of the length of shortest path between a pair of nodes *ni* and *nj*. The geodesic distance is a function of the power matrix; mathematically it can be found from the formula: $d(i,j) = \min_p x_{ij}^p > 0$ (Wassermann et al., 1994).
- *Dependency:* Index to measure how the node *ni* depends of the node *nj* when the flows go to other *nodes*. The dependency is calculated based on the betweenness centrality's process (Netminer 2005). The betweenness centrality of node *ni* is given by;

$$\sum_i \sum_i \frac{g_{ikj}}{g_{ij}}; i \neq j \neq k \ .$$

Dependency basically shows the number of times that a node *ni* needs a node *nk*, whose centrality is being measured, in order to reach a node *nj* via the shortest possible path. It can be interpreted as the control that a certain node has over the amount of flows sent to other nodes.

- *Connectivity:* Measure of the vulnerability of the network. Line connectivity between two nodes is the minimum number of arcs that must be removed to leave two nodes disconnected. Notice that the bridge concept arises from line connectivity since a bridge could leave two subsets of nodes disconnected. Node connectivity is the minimum number of nodes that if they are removed can leave a subset of nodes or the whole organization disconnected.

Subset measures: Dyad and triad

Dyads

The isomorphic contacts between two nodes in the network are called *dyads*. In fact the contact or non-contact between two nodes is a sub-network of the whole network. There are only three ways for how two nodes make contact between them; this concept is known as "isomorphism states." If in the adjacency matrix ***N*** the values of *(i,j)* and *(j,i)* are located symmetrically, the dyad is named "mutual" and it is defined as $D_{ij} = (1,1)$ (Wasserman et. al. 1994). If in the adjacency matrix ***N*** the values of (*i,j*) and (*j,i*) are located asymmetrically, then the connection between the pairs of nodes can occur in two ways, when the $D_{ij} = (0,1)$ and $D_{ij} = (1,0)$. This kind of dyad is known as asymmetric. If there are no contacts between (*i,j*) and (*j,i*), then the dyad is defined as $D_{ij} = D_{ji} = (0,0)$ and this kind of non-relationship is known as nulls dyad (see Figure 13).

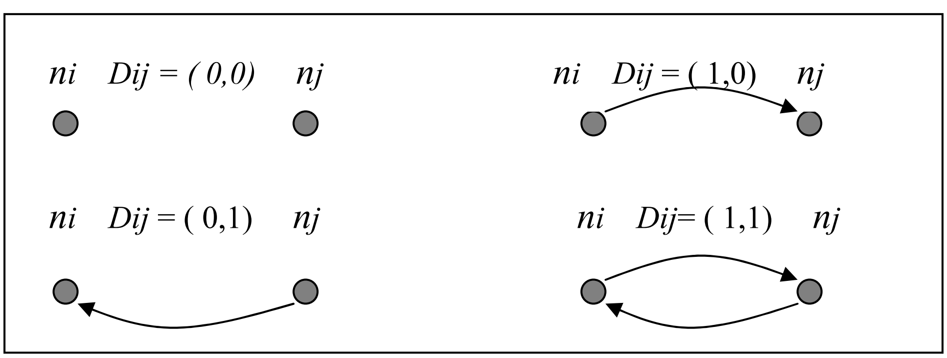


Figure 13: Isomorphic type of dyads

The implications that dyadic isomorphism types have for a simulated network centric environment are relevant, from the perspective that our methodology deals with interactions in the organization, and each isomorphism state represents if there is transference of entities between two nodes.

The distribution probabilities of the flows will depend on the nature of the node simulated. For instance, if we assume the behavior of a node *ni* which is a *tsunami sensor* located 150 miles from of the coast, we could assume that sensor has a *Dij* = (1,0) independently of the *nj*, which is being fed for the sensor.

On the other hand, we have to consider the external events which govern the behavior of each node. In the case of a sensor, it reacts to physical events produced by nature, but in the case of nodes composed by human being, they react to the procedures and rules pointed out in the emergency planning.

We may represent a *Dij* = (1, 1) as discrete or continuous flows between *ni* and *nj,* where the internal node behavior will depend on the event's magnitude and the node's position in the organization. According to this research, the dyad is the starting point to find out the performance of an emergency management organization in a networked environment. The statistical information derived from the connected pairs of nodes is defined as *dyad census*, and these indexes are a function of the matrix ***N***, where:

M= Number of mutually connected pairs of nodes and is computed according to:

$$Dij = (1,1) = (1/2)trace(NN);$$

A= Numbers of asymmetrically connected pairs of nodes and it is computed according to:

$$A = trace(NN') - trace\ (NN);$$

N = Number of not connected nodes and it is computed according to:

$$Dij = (0,0) = n(n-1)/2 - trace(NN') + (1/2)trace(NN').$$

Triads

Three nodes ($n1,n2,n3$) ε N of the graph $G = (N, L, D)$ with $L = \emptyset$, the sub-graphs derived from the set $T\ (n1,n2,n3)$ are called a triad.

We highlight a significant issue: **"***To capture the structure of a directed network, we must proceed from dyads to triads***"** (Nooy, Mrvar, Batagelj , 2005). Lets explain why we consider the previous statement significant. Under an isomorphism analysis there are sixteen classes of triads. If we consider that each isomorphism graph represents different types of flows between the three nodes, we could conjecture a causal dependency between the number of triads and the efficiency of an emergency organization. In fact there are $\binom{n}{3}$ triads in a graph with *n* nodes. Figure 14 shows the sixteen types of triads.

The standard for labeling the different types of triads is known in SNA as *MAN*. Based on the number of dyads, *MAN* convention uses three and four characters to identify the type of triad. The first *M* digit shows the number of mutual positive dyads. The second one, *A,* shows the number of asymmetric dyads, and the third, *N,* presents the number of null dyads in the triad. When required, a character is added to show if the triad is transitive *(T),* cyclic*(C),* or on its way is up *(U)* or down *(D).*

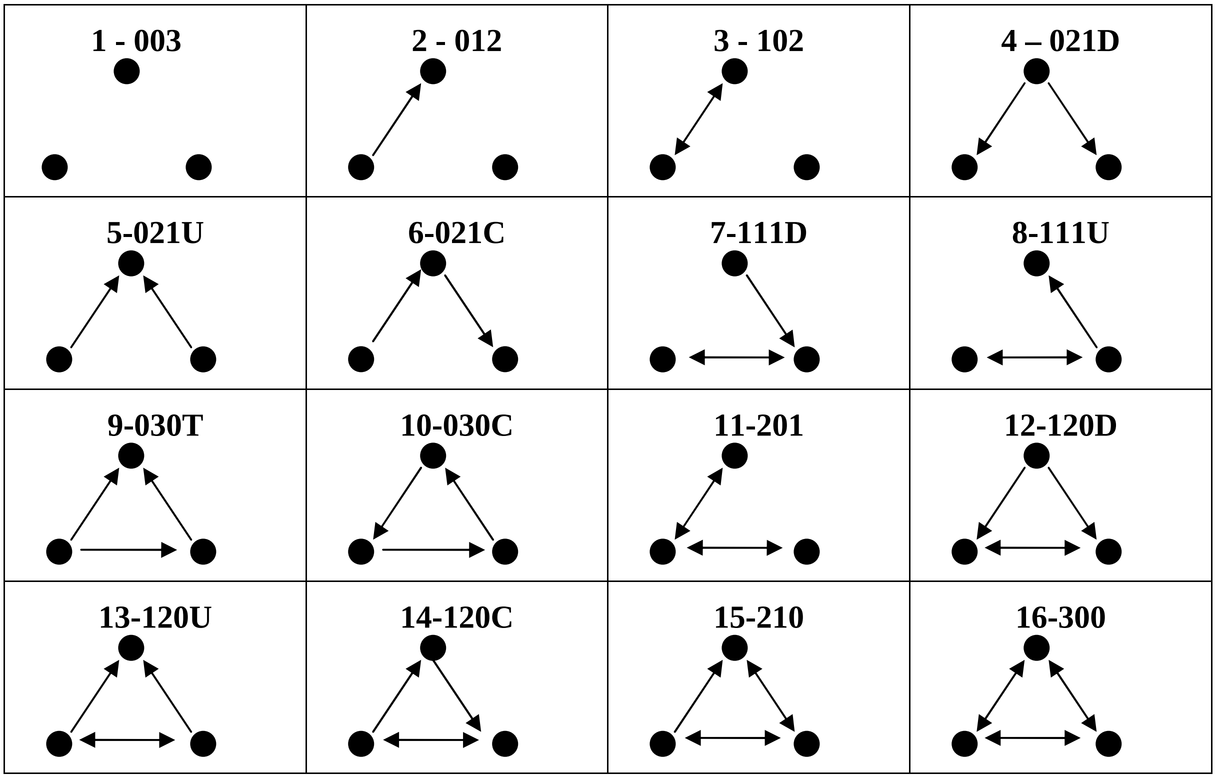


Figure 14: Isomorphism classes in a triad

The rate of repetition of each triad in a configuration is named *triad census*. It can be used to predict structural properties in the whole network. The force of the concept of triad emerges from the analysis of the sixteen types of isomorphism. Only a few networks have triad censuses that depart substantially from those generated by random networks of the same size and density. This finding reminds us that the range of possible structural patterns in a social network is highly constrained by its size and density (Faust, 2005). This assertion presents notable opportunities for fitting emergency structures composed by hundreds of nodes to random networks; nevertheless data will be necessary for testing structural hypotheses.

A similar statement is suggested by Nooy et al, (2005) who pointed out that "It has been shown that the overall structure of a directed network can be inferred from the type of triads that occur".

Both of these arguments confirm that tools exist for predicting complex network centric behavior. Thus, we could analyze the complete structure of an emergency management organization by only analyzing the digraphs formed by three nodes. Heider and later Newcomb developed the *balance theory,* which provides the foundation for interpreting the quantitative aspects yielded on triple nodes (Wassermann et al., 1991).

The following are the main features of a network studied from the perspective the *balance theory*:

- A path is a cycle in which the first and last nodes coincide.
- A cycle is a closed path
- A semi-cycle is a closed semi-path.
- A semi-cycle and cycle are balanced if they do not contain an uneven number of mull dyads.
- A digraph is balanced if all of its semi-cycles and cycles are balanced.
- A digraph is balanced if it can be portioned into two clusters such that all arcs are contained within the clusters and all null dyads are situated between the clusters.
- A cycle or semi-cycle is *clusterable* if it does not contain exactly one null dyad.
- A digraph is *clusterable* if it can be portioned into clusters such that all arcs are contained within clusters and all null dyads are situated between clusters.

The theory of *structural balance* is extremely polarized because the nodes can be grouped in only two clusters. Table 18 shows that it is possible to relax the *balanced model* in five additional levels. Although the theory of *structural balance* was intended for applying in the psychology field, it provides an invaluable mathematical foundation for capturing the interactions produced in an emergency management system.

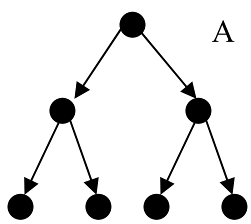
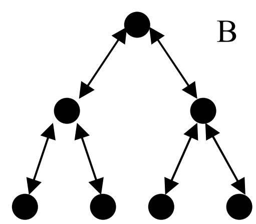
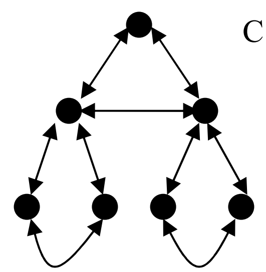
Table 18: Balanced theoretic models (Nooy et al, 2005)

Model	Arcs within a Cluster	Arcs between Ranks	Permitted Triads
Balance	Symmetric arcs within a cluster. No arcs between clusters. Max two clusters.	None	102 300
Clusterability	Symmetric arcs within a cluster. No arcs between clusters. No restriction on the number of clusters.	None	102 300 003
Ranked Cluster	Symmetric arcs within a cluster. No arcs between clusters. No restriction on the number of clusters.	Asymmetric arcs from each node to all nodes on higher ranks. Null arcs may occur between ranks.	102, 300,003, 021D, 021U, 030T, 120D, 120U
Transitivity	Idem	Null arcs may occur between ranks	102, 300,003, 021D, 021U, 030T, 120D, 120U, 012
Hierarchical Clusters	Asymmetric arcs within a cluster allowed provided that they are acyclic.	Idem	102, 300,003, 021D, 021U, 030T, 120D, 120U, 012, 120C, 210.
No Balanced – Theoretic model . (Forbidden)		Idem	021C,111D,111U,030C,201

In the context of this research, *triad census* and *balance theory* will support the analysis of the dynamic flows between the components of an emergency management organization. Since the organizational structure can be mapped to a digraph, using a simulation technique those flows will take either continuous or discrete entities produced in the nodes. Thus, this methodology merges two different techniques for understanding the complexity that arises in a networking centric scenario.

We developed two examples for testing different patterns produced in an organizational structure. The first example shows three hierarchical configurations which could be found in an ICS (see Table 19). The three configurations have seven nodes, but the rules that control the flows are given for different dyad interactions. The vector *T* shows the sixteen triads types contained in the $\binom{n}{3}$ sub-graphs of each configuration.

Table 19: Three hierarchical configurations for testing the 16 isomorphism triads

		
Mutual Dyads : 0 Asymmetric Dyads: 6 Null Dyads : 15 Density : 0.143	Mutual Dyads : 6 Asymmetric Dyads: 0 Null Dyads : 15 Density : 0.286	Mutual Dyads : 9 Asymmetric Dyads: 0 Null Dyads : 12 Density : 0.429
T_A=[12,16,0,3,0,4,0,0,0,0,0,0,0,0,0,0]	T_B=[12,0,16,0,0,0,0,0,0,0,7,0,0,0,0,0]	T_C=[4,0,20,0,0,0,0,0,0,0,8,0,0,0,0,3]

We could state that the model *A* has a low density and the relationships are asymmetric; in fact there are 16 asymmetric *dyads* and *Triad 003* and *012* populate with more frequency the vector T_A.

Could the graph *A* apply to how we validate configuration in a network centric scenario? Earlier, we defined network centric decision making as how the interactions of human beings and machines lead to decision making, then the vector T_A might perfectly represent a portion of the network composed of a set of three sensors which after checking their signals report automatically their data to four different nodes integrated by human beings.

On the other hand, configuration B and C could present many types of interpretation. We only argue one respect to the level of *situation awareness* of an emergency management organization.

Configuration *B* shows a classical ICS, with return feedback to the upper authority level in the chain of command. (The National Incident Management System recommends a span of control between three and seven nodes (NIMS, 2004).) The interactions only are verticals and it does not allow horizontal communication. The density of the network is 0.286. Configuration *C* increases the *mutual dyads in* three arcs, since that allows the interactions between nodes at the same level. Thus the density of *C* changes to 0.429.

What is the most significant difference between configuration *B* and *C*? If we analyze the level of *situation awareness* of a *commander incident*, we realize that configuration *C* provides more accurate information than configuration *B*, since the lower levels had the chance for checking *the observables hints on the ground*, and as consequence, the *commander incident* avoids confusion and duplicity of effort and he can react quickly to the variations produced in the complete scenario.

Comparing only the vectors T_B and T_C, we can say that there are two isomorphic classes that modify the behavior of the configuration *B* and *C*; they are *Triad 003* and *Triad 300*.

Network measures

- *Density:* Proportion of the number of arcs present to the maximum possible on a network.
- *Average degree:* Average degree value of all nodes in given network.
- *Inclusiveness:* Proportion of all connected nodes to the total number of nodes in the network.
- *Reciprocity:* Proportion of the maximum number of reciprocated arcs to the total number of arcs.
- *Transitivity*: The proportion of the number of transitive triads to the number of potentially triads.
- *Clustering coefficient:* Average of all nodes' clustering coefficients. For each node the number of connections that could possibly exist between these neighbors is calculated; then the proportion of the connections that actually does exit is the clustering node coefficient.
- *Mean Distance:* Average geodesic distance between any pair of nodes in a network.
- *Diameter:* The largest geodesic distance between any pair of nodes in a network.
- *Connectedness:* Proportion of nodes which are not mutually reachable and the maximum number of possible nodes unable to reach other nodes in the network.

$$Connectedness = 1 - \left[\frac{U}{N(n-1)/2} \right]$$

- *Efficiency:* A network *N* with *n* nodes is composed of Ns sub-networks. The sum of all the connections over *n-1* in *N* is known as *E*, and the sum of the maximum number of connections in *Ns* is named as *Max E.* The value of 1 minus the proportion of *E* and *MaxE* is denominated *efficiency.*

$$Network-efficiency = 1 - \left[\frac{E}{MaxE}\right]$$

- *Hierarchy:* For each pair of nodes where *ni* can reach another *nj*, the second *nj* cannot reach the first *ni.* The number of unordered pairs of nodes that are symmetrically connected is named *S* and the maximum number of unordered pairs of nodes connected between *ni* and *nj* is named *MaxS*; thus the index of 1 minus the ratio of *S* and *MaxS* is known as *Hierarchy.*

$$Hierarchy = 1 - \left[\frac{S}{MaxS}\right]$$

- *LUB (Least Upper Boundedness)*: "Within each sub-network each pair of nodes (*ni* and *nj*) has at least one least upper bound . An upper bound for a pair of nodes is a third *node nk* from which there is a path to each of the pair; a least upper bound is an upper bound *nk* that is included in at least one directed path from each other upper bound to each of the pair *(ni,nj).* Violations to this condition occur whenever a *(ni,nj)* pair of points in the sub-network has no LUB" (Krackhardt, 1994).

$$LUB = 1 - \left[\frac{T}{MaxT}\right] \quad \text{where} \quad MaxT = \left[\frac{(Nn-1)(Nn-2)}{2}\right]$$

Every sub-network has at least *Nn -1* connections and then has by definition at least *Nn -1* pairs of nodes that do have *LUB.* Krackhardt (1994) stated that *LUB* is the most complex measure to evaluate structure, since it is the only measure in a network sensitive to the direction of the nodes' connections. *LUB* enables us to study the unity of command principle in our research and to analyze the position of a decision maker in the network centric scenario.

Two-mode network: Definition and implication for NCDM

This kind of network presents two types of node sets in which the one set only can be connected to the nodes of the other set. Usually in the literature of social network a two-mode network is called membership network or hypernetwork. The affiliation relation between the set of networks is referred to as an *involvement relation*.

The first set of nodes is known as *actors* and can be denoted as: $N = \{n1, n2,..nn\}$. The second set of nodes is known as *events* and can be denoted as: $M = \{m1, m2,..mn\}$. The affiliation network matrix is called affiliation matrix and can be denoted as $A = \{a_{ij}\}$. See Table 20.

The affiliation relation between the vector N and M can also be represented by a bipartite graph (Wasserman et al, 1994) in which the socio-matrix contains only 0 and 1 and represents the association between the node and the event. See Figure 15.

Table 20: Affiliation matrix in two-mode

Actor	Event 1	Event 2	Event 3
Node 1	1	1	0
Node 2	1	0	1
Node 3	0	0	1
Node 4	1	0	0
Node 5	0	0	1

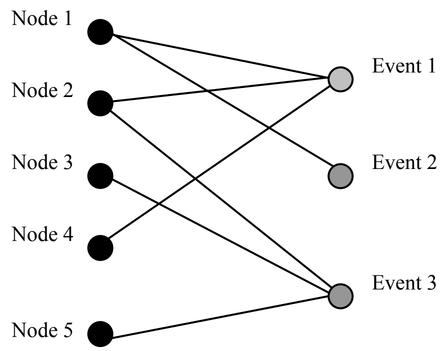


Figure 15: Bipartite graph to a two-mode network

Sometimes the nodes in a network centric scenario are involved in more than one simultaneous task. For instance the chief of a department of police, from his command post, could be making a decision regarding an incident that happened in sectors A and B of his local jurisdiction simultaneously. In this case a two-mode network could provide a better understanding of the behavior shown by the decision maker (chief of police) when dealing with two or more events concurrently. We describe a set of six two-mode metrics (Wasserman et al, 1994):

- Rate of participation
- Reachability
- Event Size
- Diameter
- Density
- Connectedness

All the measures above are calculated over the bipartite graph but using the technique mentioned in one-mode network; nevertheless we need to keep in mind that we analyze the participation of a set of nodes in sets of simultaneous extreme event.

Finding measures for testing in an incident command system

According to the summarized analysis made over the five extreme events (Kobe Earthquake, Oklahoma Bombing, Mitch Hurricane, Chernobyl nuclear accident, and Hurricane Katrina) we could identify only in the case of Hurricane Katrina that the authorities had a well defined general plan for dealing with an extreme event, which is known as National Incident Management System.

In the others four incidents, there did not exist a clear plan of response, and there also did not exist any system for integrating the different agencies, authorities, volunteers and non governmental organizations that were worked on site.

The first question that arises is how can we apply the network metrics in a real scenario such as the previously studied?

Initially, if an organization has a formal structure with systematized procedures tested in a training system, then we argue that the emergency management system can be analyzed analytically in the time *T-* (before the extreme event occurs) by using the mentioned metrics combined with LP technique.

From the T_0 (time that the alert system is activated) we will require data coming from the database of the organization. Those data correspond to the interactions produced in a real time environment and should contain all the attributes necessary for populating the matrixes of a hybrid simulation model. Figure 16 shows a schema in which the *triad i, j, k* performs the interactions by means of an isomorphic class type 300.

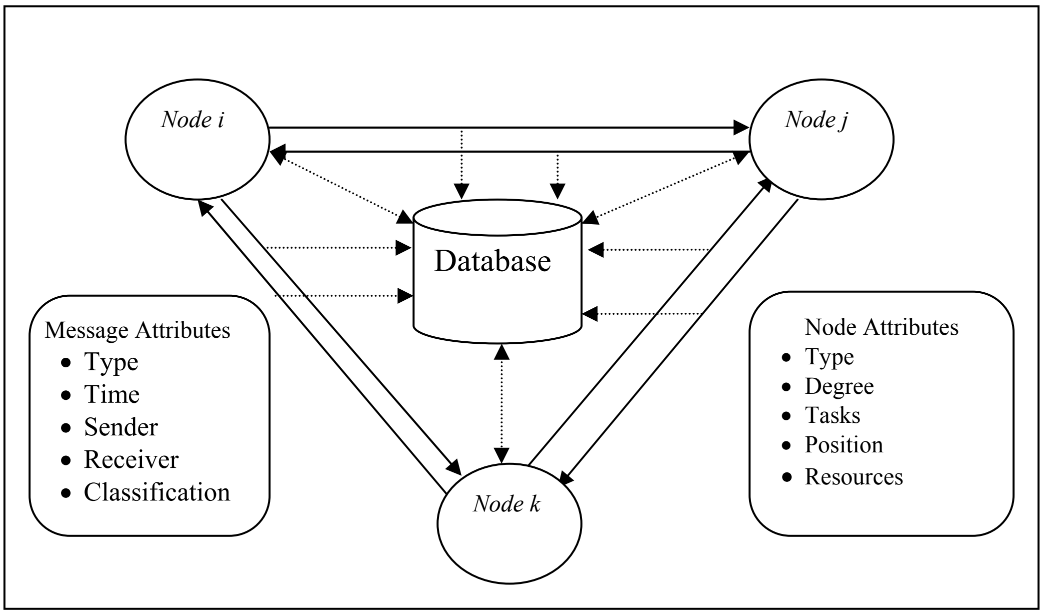


Figure 16: Model for capturing the interactions of the triad *i, j, k*

The process for collecting the information stored in the database with the attributes of the nodes *i, j* and *k* can generate plausible arcs which represent the interactions and their attributes. Notice that the scheme shown in Figure 16 is relatively simple to implement whether the organization has available either a command and control system or a training system for collecting data coming from an *organization in the loop.*

Since the dyads are not persistent during the development of a crisis, the relationships between two nodes could be in three different states: *mutual*, *asymmetric* or *null.*

Therefore, we suggest that the systems more suitable for capturing those dynamics states are built over information technology.

According to the network classification, a second question arises in our methodology: Could an emergency structure fit either a random or scale free network?

We proved that the organization structure is well defined in the EOP and ICS. Thus, nodes, positions, sequences and arcs can be collected from those documents and mapped to a simulated network. At this point, there are no dynamic interactions among the nodes, but surveys, interviews and analyses of the historic incidents could be useful tools for fitting the layout of the organization to a network model whose statistical parameters are known.

On the other hand, once that emergency management organization is activated, the relationships between the nodes change according to how the situation evolves. Here we will require the mentioned systems based on technology of information for gathering those interactions. For instance, suppose that the different components of the organization can be fitted with a random network of size *n* and number of connections *l,* and suppose that we found that the uniform distribution is the best suitable distribution for analyzing the complex nodes' interaction in the organization. Using the equation *P (N=n),* we could generate the adjacency matrix *A* distributed as a uniform random variable.

$$P(N=n)=\left[\frac{1}{2^{n(n-1)}}\right]$$

For comparing how the parameters affect the organizational structure of the random network and its measures of performance, we defined a *longitudinal network* in four moments of its evolution:

- Timeframe 1: Random network with eight nodes and sixteen arcs. Density equal to 0.28.

- Timeframe 2: Random network with sixteen nodes and thirty-two arcs. Density equal to 0.13.
- Timeframe 3: Random network with thirty-two nodes and sixty-four arcs. Density equal to 0.06.
- Timeframe 4: Random network with sixty-four nodes and one hundred twenty-eight arcs. Density equal to 0.03.

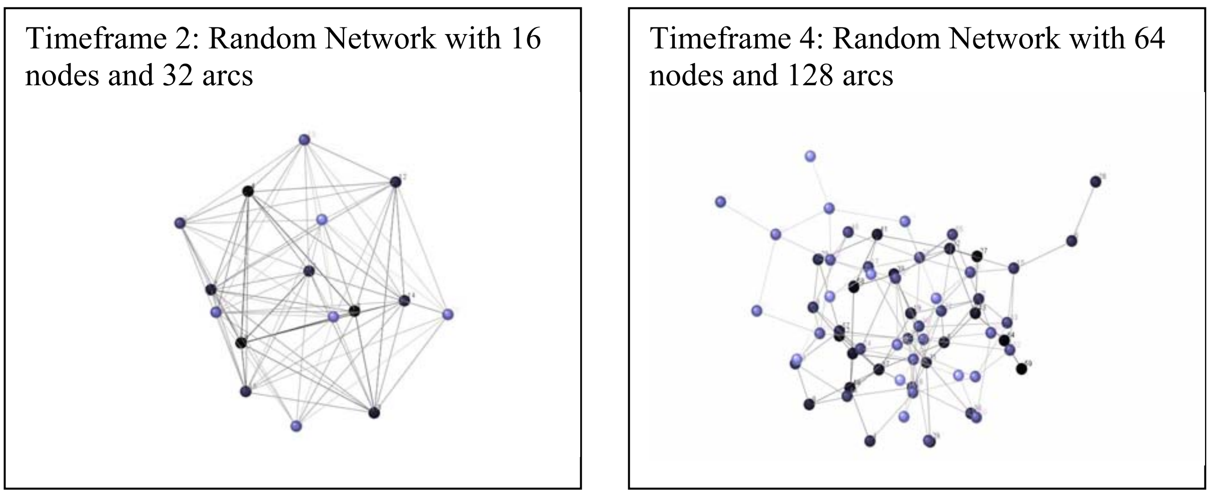


Figure 17: Longitudinal network generated with uniform distribution

Table 21 shows eleven metrics found in the longitudinal network. We can identify dependent patterns in the four moments of the random network. The growth of the longitudinal network is explained by the incorporation of new nodes to the structure according to the evolution of the extreme event.

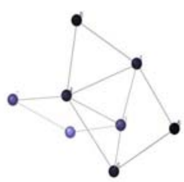
Table 21: Metrics obtained from four uniform random networks

Nodes	Arcs	Density	Inclusi-veness	Recipro-city	Transitivity	Clustering Coefficient	Mean Distance	Diame-ter	Connecte-dness	Effici-ency	Hierarchy	LUB
8	16	0.28	2	1	0.27	0.64	2.08	5	0.75	0.816	0.25	1
16	32	0.13	1	0.25	0.07	0.19	2.63	6	0.30	0.92	0.67	0.9
32	64	0.06	1	0.06	0.05	0.17	4.72	11	0.423	0.96	0.53	0.91
64	128	0.03	1	0.03	0.02	0.09	4.34	10	0.427	0.98	0.48	0.90

An alternative model was generated based on the parameters of a *scale free network*. We assume that the evolution of the structure of the organization follows a *power law* behavior. In order to test the same metrics used for a random network, we generated the second longitudinal scale free network based on the following parameters:

- Timeframe 1: Scale free network with eight total nodes and two starting nodes. Density equal to 0.21.
- Timeframe 2: Scale free network with sixteen total nodes and four starting nodes.. Density equal to 0.10.
- Timeframe 3: Scale free network with thirty-two total nodes and eight starting nodes. Density equal to 0.04.
- Timeframe 4: Scale free network with sixty-four total nodes and sixteen starting nodes. Density equal to 0.02.

Timeframe 1: Scale free network with 2 initial nodes and a total of 8 nodes.



Timeframe 4: Scale free network with 16 initial nodes and a total of 64 nodes.

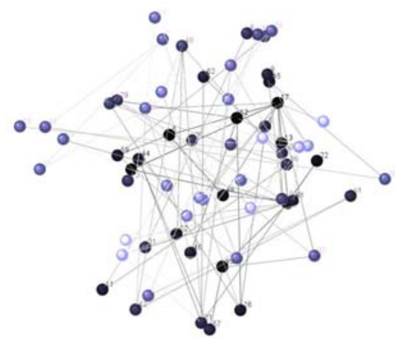


Figure 18: Longitudinal scale free network

Table 22: Metrics obtained from four scale free networks

Nodes	Arcs	Density	Inclusiveness	Reciprocity	Transitivity	Clustering Coefficient	Mean Distance	Diameter	Connectedness	Efficiency	Hierarchy	LUB
8 (2)	12	0.21	1	0	0.125	0.271	1.65	3	0	0.898	1	1
16(4)	24	0.10	0.93	0.0	0.12	0.19	1.61	3	0.0	0.94	1	0.50
32(8)	48	0.04	0.96	0.0	0.033	0.07	2	5	0.0	0.98	1	0.37
64(16)	96	0.02	0.95	0.0	0.008	0.036	2.46	6	0.0	0.99	1	0.30

Table 22 shows eleven metrics found in the longitudinal scale free network. We can identify dependent patterns in the four moments of the scale free network. With similar arguments we can say that the growth of the longitudinal network is explained for the incorporation of new nodes to the structure according to the evolution of the extreme event.

Applying linear programming in a network centric scenario

The after action analyses carried out for understanding why a huge organization, such as an ICS, performs well or bad facing an extreme event always have been made from a qualitative perspective and those analyses never consider analytic tools with numerical results that support the conclusions of the analysts and stakeholders.

In Appendix A we show that the five cases of extreme events do not consider any form of quantitative analysis that permits the enhancement of expensive and complex emergency systems which are usually composed by human beings and intelligent machines.

The Vincennes incident is the exception to the rule, because extensive, detailed and quantified studies were conducted to determine why a very well-trained crew equipped with an advanced fire-control defense system failed at a critical event. Those numerical results were used to improve the human-system interaction technologies and to design better decision support systems.

Our proposal hereby is a hybrid approach that combines different techniques for enhancing the analysis and collaborative response to the disasters. In this context we suggest that LP is one of the techniques (likely the most rigid, but best understood) for improving the structures of an ICS and also for evaluating the performance of nodes at the federal, state and local levels.

Notice that throughout this research, we emphasize the word *hybrid*, which applies such as the combined interpretation of the role and position of the nodes involved in a LP and SNA.

We have identified four main features that are conducive for applying LP in an incident management system:

- Standardized incident protocols and procedures documented in the EOP which are mandatory for all responders at federal, state and local-levels to conduct and coordinate response actions.
- The implementation of the ICS under the concept of *unity of command* which specifies that "each person within an organization reports to one and only one designated person" to ensure unity of effort under one responsible commander for every objective (NIMS, 2005).
- The necessity of integrated planning at the federal, state and local levels, given that the incidents are managed at the lowest jurisdictional level possible, and the upper levels are involved as soon as the situation reaches state or national significance.
- The incident command systems work over a network centric environment and the networks are well situated to analyze with linear programming.

We suggest three LP models among many other possibilities and we propose to enhance the interpretation of the LP outcomes by means of SNA technique; signal path optimization (network flow), deployment of resources (allocation) and data envelopment analysis (evaluation of performance).

In Appendix B, we show the adjacency matrix which represents a theoretical structure of an ICS with 37 nodes. Each node must belong to the federal, state or local level. In social network terminology, the classification levels are known as a *partition* and it must be incorporated as an attribute vector of the adjacency matrix. Thus the digraph is shown in Figure 19 according to the centrality values nodes and their partition attributes.

At the federal level, blue nodes are governmental decision makers and agencies. At the state level green nodes correspond to organizations and agencies, and finally, at the local level, red nodes correspond to task forces, mayor, incident commander, police, fire-rescue, private organizations, etc.

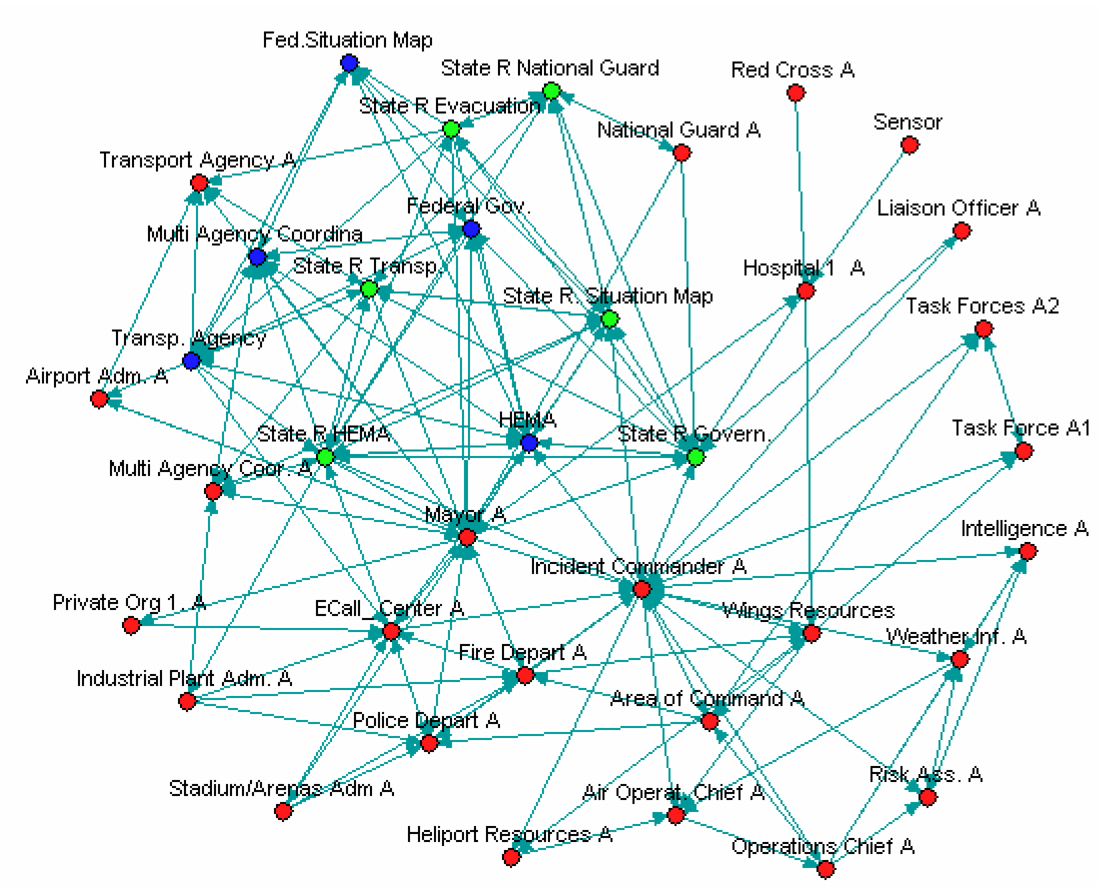


Figure 19: Digraph of an incident command system at federal, state and local levels

By simple visual inspection, we can distinguish the high centralization of two nodes in the local level: the *incident commander* and the *mayor*.

At the state level, the *governor* is the node with the most incident connections and at the federal level, the *High Emergency Management Agency* has the most incident connections.

One of the most recurrent problems in an ICS is interoperability jurisdiction, which implies clear delimitation of authority levels, coordinated procedures, balanced assignation of tasks and synchronized transferring of flows and resources from federal to the state and local levels. In order to demonstrate how the study of a network centric environment is enhanced by using LP and SNA, we suggest the use of the Gould and Fernandez's brokerage measures to analyze jurisdictional roles of the nodes in a network centric environment. By using the partition vector, the brokerage index counts the number of times each node is involved in five kinds of brokerage: coordinator, gatekeeper, representative, itinerant, and liaison relationships (Gould, & Fernandez, 1989; Netminer, 2005).

Suppose we want to optimize the warning alarm flows sent simultaneously by the nodes *Sensor, Police Department, and Hospital 1*. In accordance with the ICS rules and the EOP, we could arbitrarily state that those data must be first known by two nodes at the local level, three nodes at the state level, and two nodes at the federal level.

A number of twelve alerts (*si*) are sent by the three local nodes (gray color). Seven nodes (white color) feed different number of alerts (*si*) such as is shown in Figure 20.

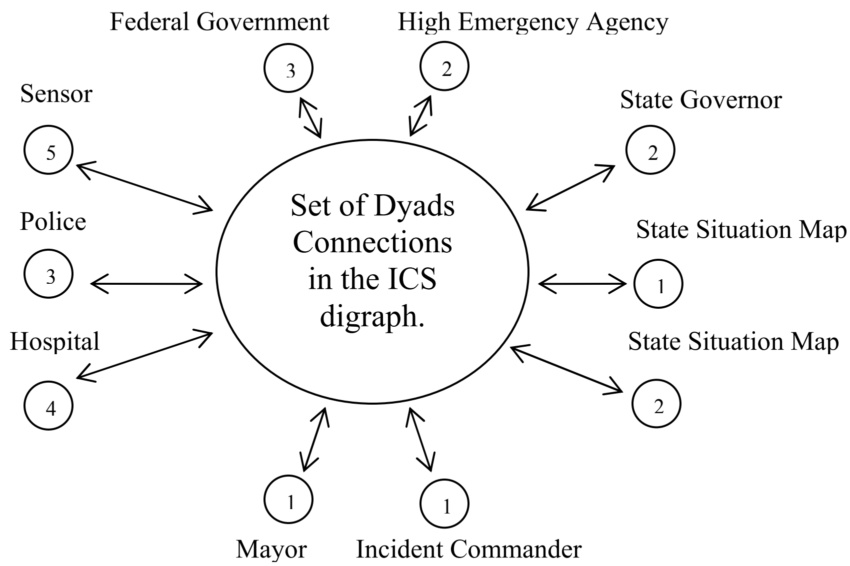


Figure 20: Sender and receptor nodes at three levels

The signal path optimization problem can be formulated as a classical *minimum-cost network flow,* where the sender nodes provide certain numbers of warning alert signals (*si*) and the receptor nodes feed an exact number of *si* to make decisions about activating the ICS in its *ego-digraph* (dyads connections of the receptors nodes).

We assume the cost of the connections of each dyad is a function of the quality of the link and the performance of the nodes.

To apply LP the number of alerts sent must be equal to the number of alerts fed by the nodes, which is represented by the equation:

$$\sum_{i=1}^{12} s_i = 0$$

If there is an unbalanced alert flow yielded and fed in the digraph, we can apply the classical technique of dummy variables. Notice that the 27 nodes, which are not considered in Figure 20, play the significant role of transshipment in the digraph.

By defining the decision variables such as:

x_{ij} = Number of alerts from the node *i* to the node *j* along connection *i, j* in the digraph.

The minimum cost problem to optimize the warning alert system in the ICS is defined:

$$\text{Minimize } z = \sum_{(i,j)\mathcal{E}D}^{177} c_{ij} x_{ij}$$

$$\text{Subject to: } \sum_{(i,j)\mathcal{E}D} x_{ij} - \sum_{(j,i)\mathcal{E}D} x_{j,i} = si$$

$$x_{ij} \geq 0 \text{ for all } (i,j) \in \text{digraph.}$$

The objective function generates the total cost of the selected paths in the digraph, and the x_{ij} variables show the optimized path for transferring the data from the sender nodes to the receptor nodes.

Early in the research, we defined the structure of the ICS, in which a vector *partitions* reminder us that we are working at three levels of decision making: federal, state and local. How could we know the patterns of jurisdiction in the ICS due to the implementation of the optimized path obtained through LP?

In order to deal with the number of times each node is involved in jurisdictional paths, we use brokerage's measures to define the patterns of each node in the ICS depending if they belong to the federal, state of local level.

Figure 21 shows the five brokerages in the context of an ICS.

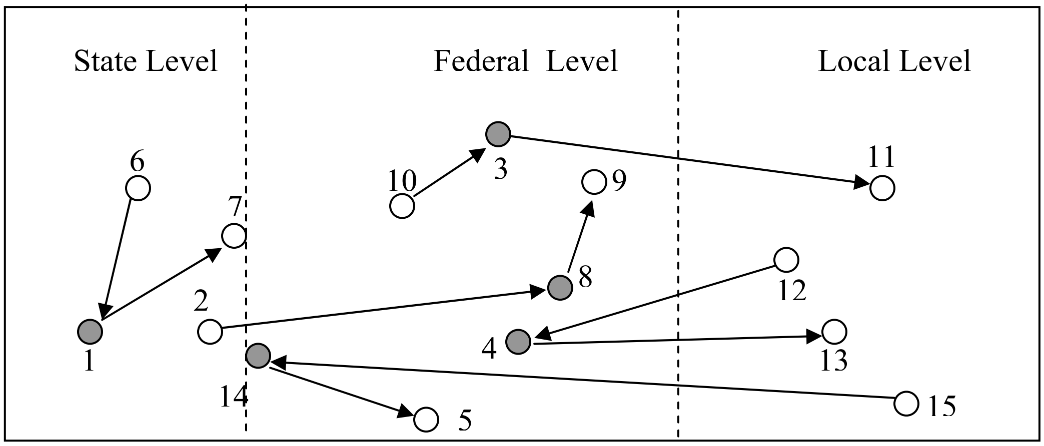


Figure 21: Type of brokers according to Gould and Fernandez's measures

1. Coordinator (n_1). Counts the number of times node 1 is a broker:

$S(n_6) = S(n_1) = S(n_7)$ (State jurisdiction).

2. Gatekeeper (n_8). Counts the number of times node 8 is a broker:

$S(n_2) \neq F(n_8) = F(n_9)$ (Federal and state jurisdiction).

3. Representative (n_3). Counts the number of times node 3 is a broker:

$F(n_{10}) = F(n_3) \neq L(n_{11})$ (Federal and local jurisdiction).

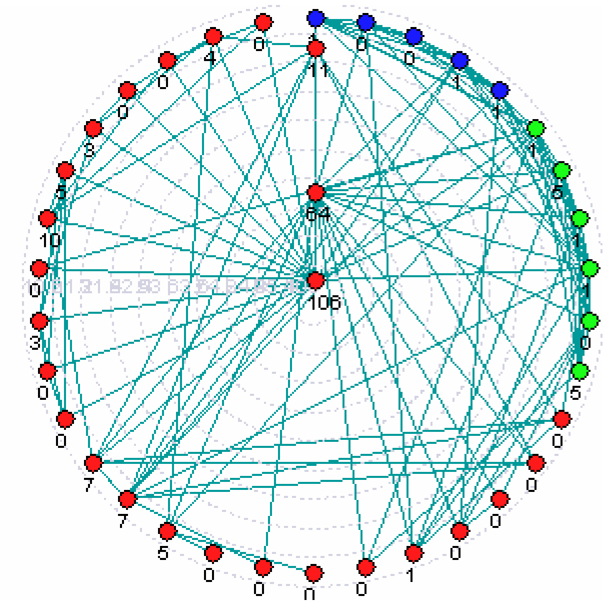
4. Consultant (n_4). Counts the number of times node 3 is a broker:

$L(n_{12}) \neq F(n_4) \neq L(n_{13})$ but $L(n_{12}) = L(n_{13})$ (Federal and local jurisdiction).

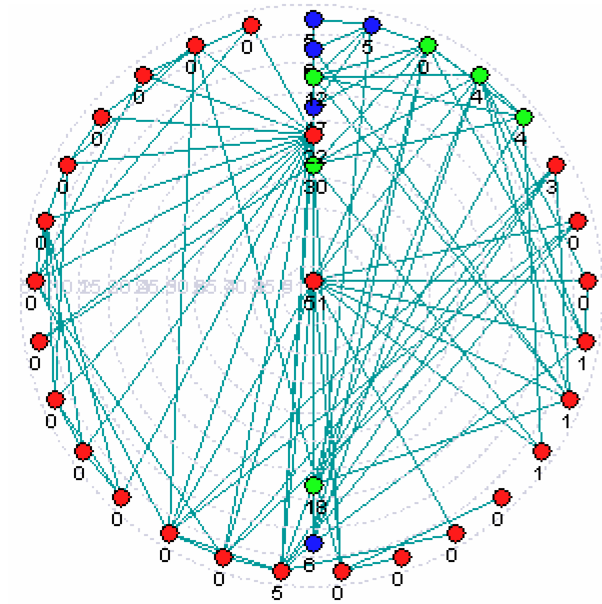
5. Liaison (n_{14}). Counts the number of times node 14 is a broker:

$S(n_{14}) \neq F(n_5) \neq L(n_{15})$ (Federal, state and local jurisdiction).

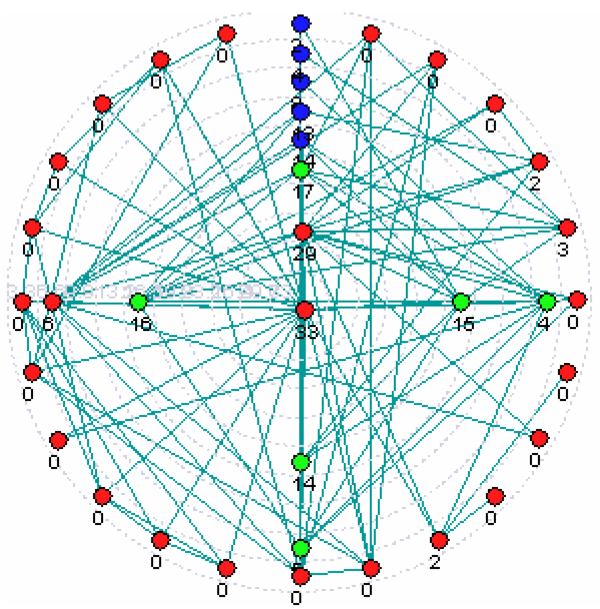
Figures 22 and 23 show the two main nodes with the highest scores in the ICS diagraph according to Gould and Fernandez measures.



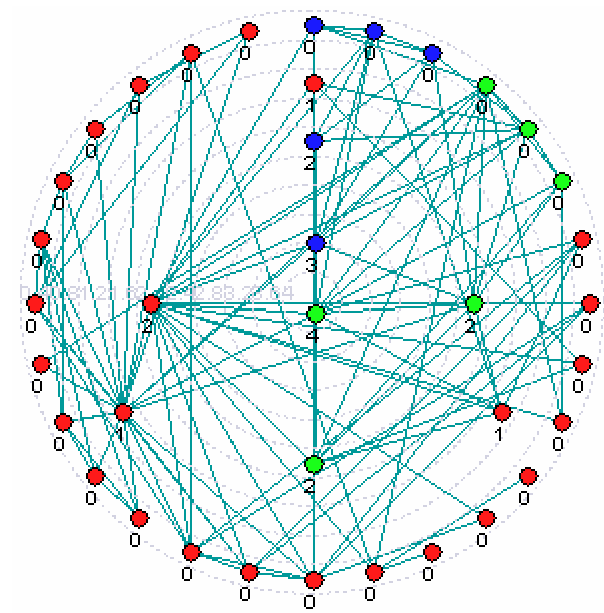
Brokerage :Coordinator
Incident Commander = 106
Mayor = 64



Brokerage: Gatekeeper
Mayor = 51
State Government. = 30

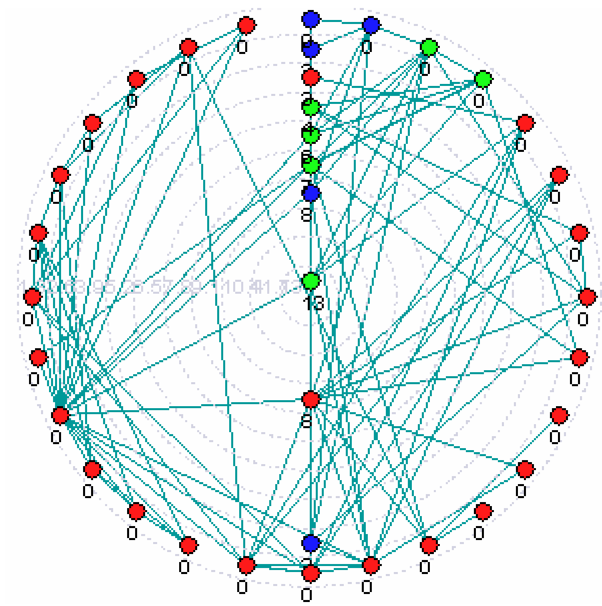


Brokerage :Representative
Incident Commander = 33
Mayor. = 29

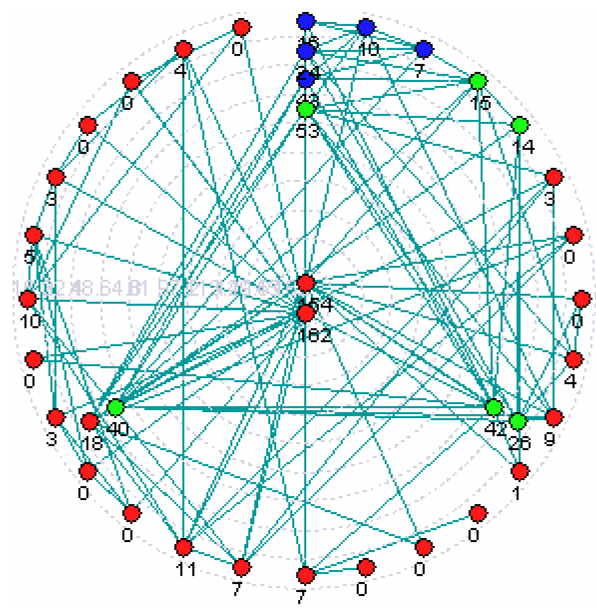


Brokerage :Itinerant
HEMA = 3
State HEMA = 2

Figure 22: Four brokerages measures in the Incident Command System



Brokerage :Liaison
State HEMA = 13
Mayor. = 8
HEMA=8



Brokerage :Total
Incident Commander = 162
Mayor. = 154
State HEMA=53

Figure 23: Brokerage liaison measure and total brokerage measure in the ICS

The brokerage role in the optimized path enables us to test hypotheses to understand how the jurisdictional problems arise in the ICS. For instance if a determined brokerage dominates in a path, then the signal alert could require more or less time according to the interoperability of the components in the vector partition (jurisdictional levels). On the other hand, if we analyze the internal composition of a broker (node) then we could acquire awareness whether the node is prepared to carry out the broker role and its associated tasks. Thus, we have demonstrated as a combined interpretation of the Gould and Fernandez's brokerage measures and the results of a

LP model can provide additional information to validate optimized transactions over the structure of an ICS.

So far we have worked with the topological representation of an ICS and nothing has been stated regarding the incorporation of geographic measures in a networked emergency organization. The identification of LP models in the deployment of resources and command post enables decision makers to solve potential difficulties during the period that the extreme event affects the geographic area.

We mentioned that in the pre-event scenario, the social network technique is a good tool for analyzing the different relationships between the organizational nodes (topological analysis), but this technique is not enough for analyzing these issues:

- Are the federal resources well placed to augment state and local capabilities due to an extreme event?
- Are the C2 systems geographically well located and topologically well assigned to the different nodes in the digraph?

Thus LP could help to select a number of clusters for placing logistic areas and command post facilities to provide resources in better way to the nodes affected for an extreme event.

By using the ICS digraph (Appendix B), in Figure 24 we describe a LP model to select three logistic areas from six propose. Assuming that the optimal solution areas are controlled by the nodes: *Industrial Plant A*, *Airport Adm.* and *State Transport*, in Figure 24 we show the geographic and the centrality deployment of the three nodes (yellow circles).

$$\sum_{i=1}^{34}\sum_{j=1}^{6} d_{ij}\cdot x_{ij}$$

$$\sum_{j=1}^{6} y_j \le 3; \qquad \sum_{j=1}^{6} x_{ij} = 1 \text{ for all } i \; ; \qquad x_{ij} - y_j \le 0 \text{ for all } i,j$$

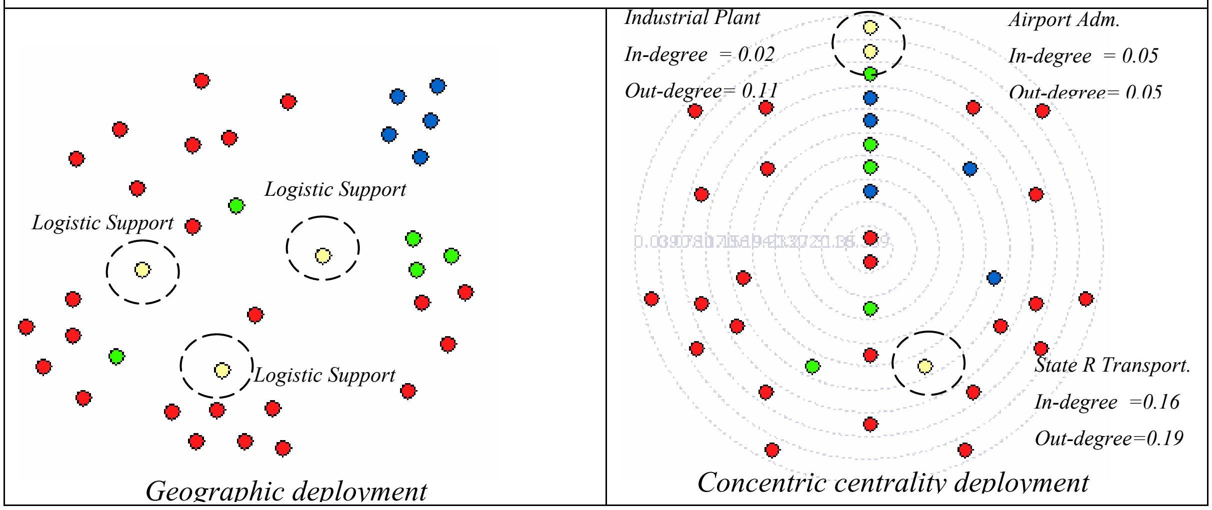


Figure 24: Deployment of resources in the ICS geographic and centrality areas

The LP model and the centralities results enable us to conclude regarding to the interpretation of the optimal logistic areas and their centralization in the structure.

Since the ICS digraph has an asymmetric adjacency matrix, the three nodes depict in-degree and out-degree centrality values, which are shown in Figure 24. Notice in the concentric deployment the weak positions of the nodes *Industrial Plant and Airport Adm*.

Therefore the combined analysis suggests that even though the so-called *logistic nodes* are the best situated geographically for supplying the ICS, their centrality values are low and easily they could be unreachable for other nodes in the information domain. As a consequence of this issue, many of the problems exposed in the Appendix A *Disaster Analysis* could happen again in an emergency structure. Besides of the degree centrality measures three additional indexes can be used for testing a combined LP and social network analysis: closeness, betweenness and eigenvalues (Those were defined in the first part of this chapter).

We have used an individual centrality measures to enhance the LP analysis; nevertheless there exists three overall degree indexes, which explain the degree centralization of the whole ICS, they are: in-degree centralization, out-degree centralization and degree centralization.

In the digraph, the in-degree and out-degree centralization scores are 0.21 and its associated total degree is 0.18. The measures provide us a representation of the digraph configuration and allow comparing the structure with another digraph of the same size (a start configuration obtains a score of 1). Thus a LP analysis should be aware of either robustness or weakness of the digraph derived of the overall centralization values.

The lack of quantitative analysis in the after action review of the extreme event is extensive to the evaluation of the efficiency in the components of the digraph. We suggest DEA as a tool to measure the relative efficiency of the nodes with the same goals and objectives in the ICS.

In Chapter Three we defined three types of events, (IE, PE and UE) and we characterized the last one as a universal event that affects the whole ICS, at different levels and places.

When a universal event occurs, it will be common to find multiple nodes with the same roles and objectives at different location, for instance multiple either fire-rescue teams or hospital facilities integrated in the ICS. In DEA terminology those nodes are decision making units (DMUs).

In order to determine the efficiency of the DMUs, the logic of DEA model allows determining whether a composite node can achieve the same or more output while requiring less input. We summarize the process in five steps (Anderson, et al., 2000; Mollaghasemi & Pet-Edwards, 1997):

- To create a hypothetical composite node based on the outputs and inputs for the nodes which have the same goals.
- For each node output measure, the output for the composite units is determined by computing a weighted average of the corresponding outputs.
- For each input measurement, the inputs of composite nodes are determined by using the same weights to compute a weighed average of the corresponding inputs for all nodes.
- Constraints in the LP model require all outputs for the composite unit to be greater than or equal to the outputs of the nodes being evaluated.
- The node being evaluated is inefficient if the input for the composite node is shown to have the same, or more output for less input. In other words, if efficiency is less than 1, the composite node does not need as many resources as the node being evaluated to produce the same level of outputs.

In the context of an ICS, the identification of DMUs is not enough, because DEA does not consider the position of the DMUs in the organizational structure, thus nodes in a better topological position could improve their outputs and decrease their inputs. We suggest the use of REGGE algorithm (regular resemblance) to identify that two or more nodes are regularly equivalent if they are equally related to equivalent others. The result of REGGE is a symmetric similarity matrix which provides a measure of regular equivalence in the digraph. This matrix is automatically submitted to a single link hierarchical clustering routine (Netminer, 2005; Borgatti, Everett &Freeman, 2002).

Figure 25 shows the hierarchical clustering of the equivalent nodes in the digraph, which enable us to apply DEA to the DMUs with the same goals and objectives.

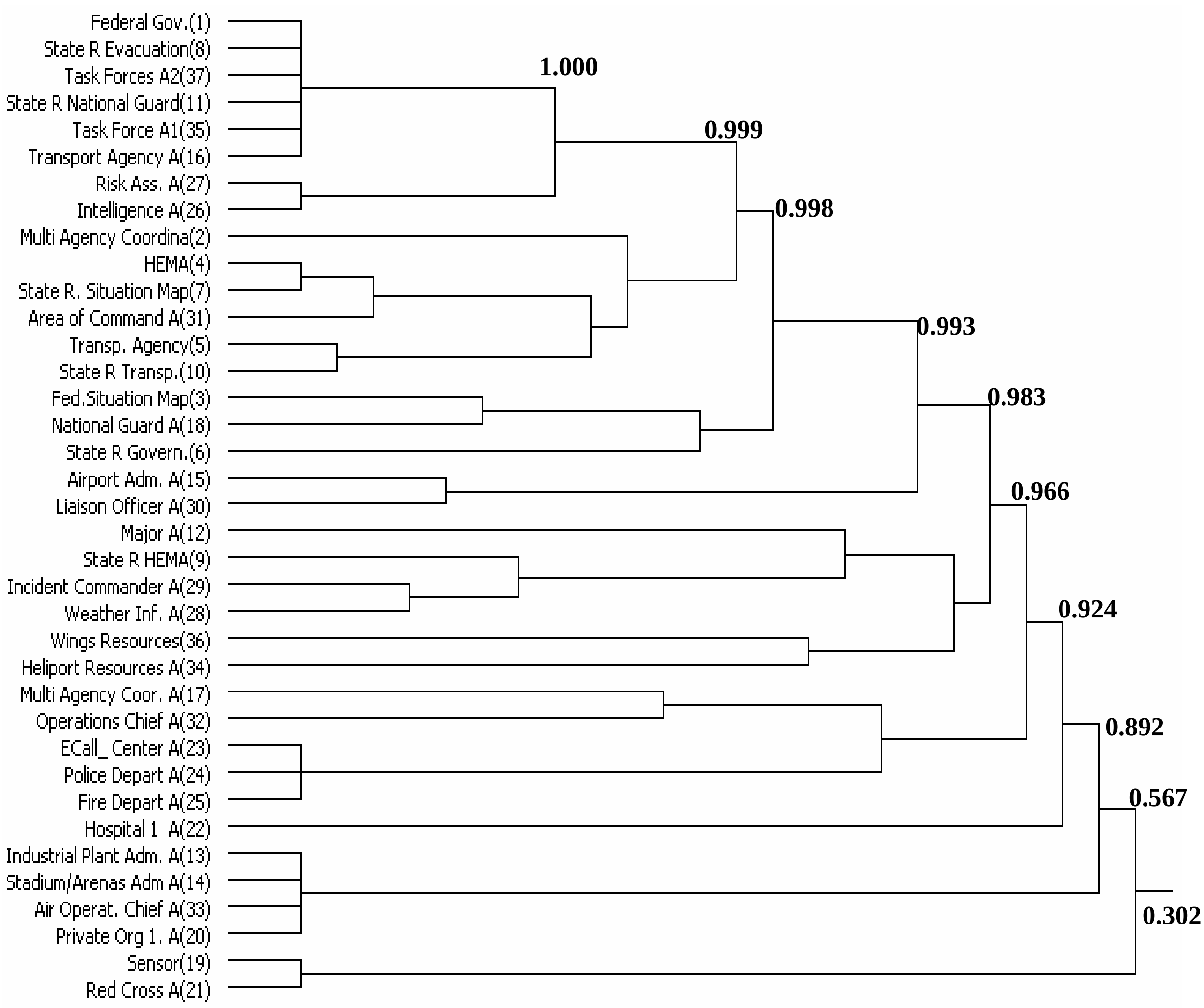


Figure 25: Hierarchical cluster of the regular equivalence of the nodes

Conclusion

In this chapter we defined three domains for evaluating the behavior of an emergency management organization that performs its tasks over a networked environment.

Using graph theory and the interpretation of the relationships given by social network technique, we defined a level of aggregation based on the concept of nodes and arcs. The methods selected enabled us to deal with the entire organizational structure rather than samples. The term *one-to-one* mapping will be used for identifying the level of granularity in our methodology.

We provided a comprehensive classification of networks and measures which can be applied to the emergency management organization. Several index measures explained the concepts of centrality, neighbor and connection.

We showed that if data is available, then a test of hypothesis by using Monte Carlo simulation could provide a statistical model for predicting the future performance of an emergency organization.

An invaluable tool was analyzed by implementing the concept of *dyad census* and *triad census*. We supported the idea that relaxing the theory of *structural balance* could know the complete structure of an emergency organization and likely to project future organizational behavior, nevertheless testing the hypothesis over the organizational data is required to validate our assumptions. (In the field of social behavior, this technique is well explained by Wasserman et al. 1994; Nooy et al. 2005).

We tested eleven network measures using random network and scale free configurations. After modifying the density of both networks, we realized that patterns arise when we change the size and number of arcs in the network. Thus we can expect that similar patterns might be found in the dynamic structure of an emergency management organization.

Finally, we proposed to incorporate LP in the optimization of an ICS. By using three examples, we demonstrated the helpfulness of a combined analysis between LP and social network measures.

CHAPTER FIVE: COMBINING SIMULATION TECHNIQUES AND CONCEPTUAL-OPERATIONAL MODEL

Introduction: Interaction between system dynamics and discrete simulation

Network centric scenarios evolve dramatically according to the evolution of the discrete and continuous environments variables, and this produces new dyadic configurations in an emergency management organization.

Most of the natural extreme events present a continuous progress over time. However, sometimes human beings do not realize that, and they perceive the evolution of the events as discrete spatial-temporal changes. On the other hand, the majority of the man-made extreme events are carried out in a specific place and time, because they are intended for producing panic and physical damage in a selected location. According to those characteristics, we classify the man-made extreme events mainly as discrete events.

In this research context, the organizational behavior can be viewed from two perspectives, the external and internal behaviors. The former are the *dyads'* transactions made between the *nodes*, such as message chains, tasks, signals, missions, and movement of resource, all of which can be represented as discrete flows of entities. The latter are the internal processes carried out in each *node*, an aspect that suggest modeling as continuous and discrete variables.

Rogalski (1991) pointed out that situations of emergency management can be considered as specific cases of dynamic environments, in which the notion of *operational flows* in any model of distributed decision making is a function of time. By *operational flows,* he defined the "environment states, cognitive tasks, material tasks to be performed and on the other, networks of organization for communication and resources."

In agreement with the previous statement, this section presents several approaches for merging SD and DES techniques. In fact, we identify the mechanisms for interacting continuous and discrete variables for getting a specific behavior. After that, we propose how to use those mechanisms for modeling several components of the network centric scenario, leaving open the methodology for implementing other models using the hybrid approach.

In this research context, we do not discuss the foundation of SD and DES, and assume a previous knowledge regarding both techniques. We will focus on the *state transition* technique and the identification of the best candidate for modeling and simulating the interactions in a network centric scenario and the internal nodes processes. Advantages and disadvantages of the named techniques will be presented.

Finally, we present a conceptual and operational model for simulating a networked decision making scenario.

System dynamics technique (SD)

The SD technique is based on a clear structure of differential equations and auxiliary variables. The interactions of the *levels*, *inflows*, *outflows*, and parameters yield a complexity that grows rapidly with the size of the model and the number of feedback loops in the system. Thus, simple systems can reach exorbitant and uncontrollable non-linear behaviors in the variables of states (levels).

Kampman pointed out, "It is still an open question whether the feedback loops concept is useful in large-scale systems" (Kampmann, 2004). Even so, SD presents many features which might be useful for modeling *nodes* and their interactions in a networked scenario. For instance, the variable of state named *level* shows four useful features (Adapted with modifications of US. Department of Energy, 2006):

- Have memory: Variable of state conserves the number of entities if the inflow and outflow are constants.
- Change the time slope of flows: When there exists a feedback loop between level and inflow or outflow, the behaviors of both are modified.
- Decouple inflows and outflows: Enables control of the entities by different variables of the model.
- Create delay: Enables interruption of process of data and resources in time.

Many attempts have been made to reduce the complexity of the structural behavior derived from many feedback loops. Research efforts have identified nine types of feedback loop structures named *archetypes*, because they describe similar patterns previously found in different SD models.

Senge (1990) described a set of archetypes to recognize, and modifying specific feedback loops in a system. Wolstenholme (2003) summarized those archetypes in four models based on the two basic types of feedback loops (balancing and reinforcing), as shown in Figure 26:

- Underachievement: The intended achievement fails to be realized.
- Out of control: The intended control fails to be realized.
- Relative achievement: The achievement is only gained at the expense of others.
- Relative control: The control is only gained at the expense of others.

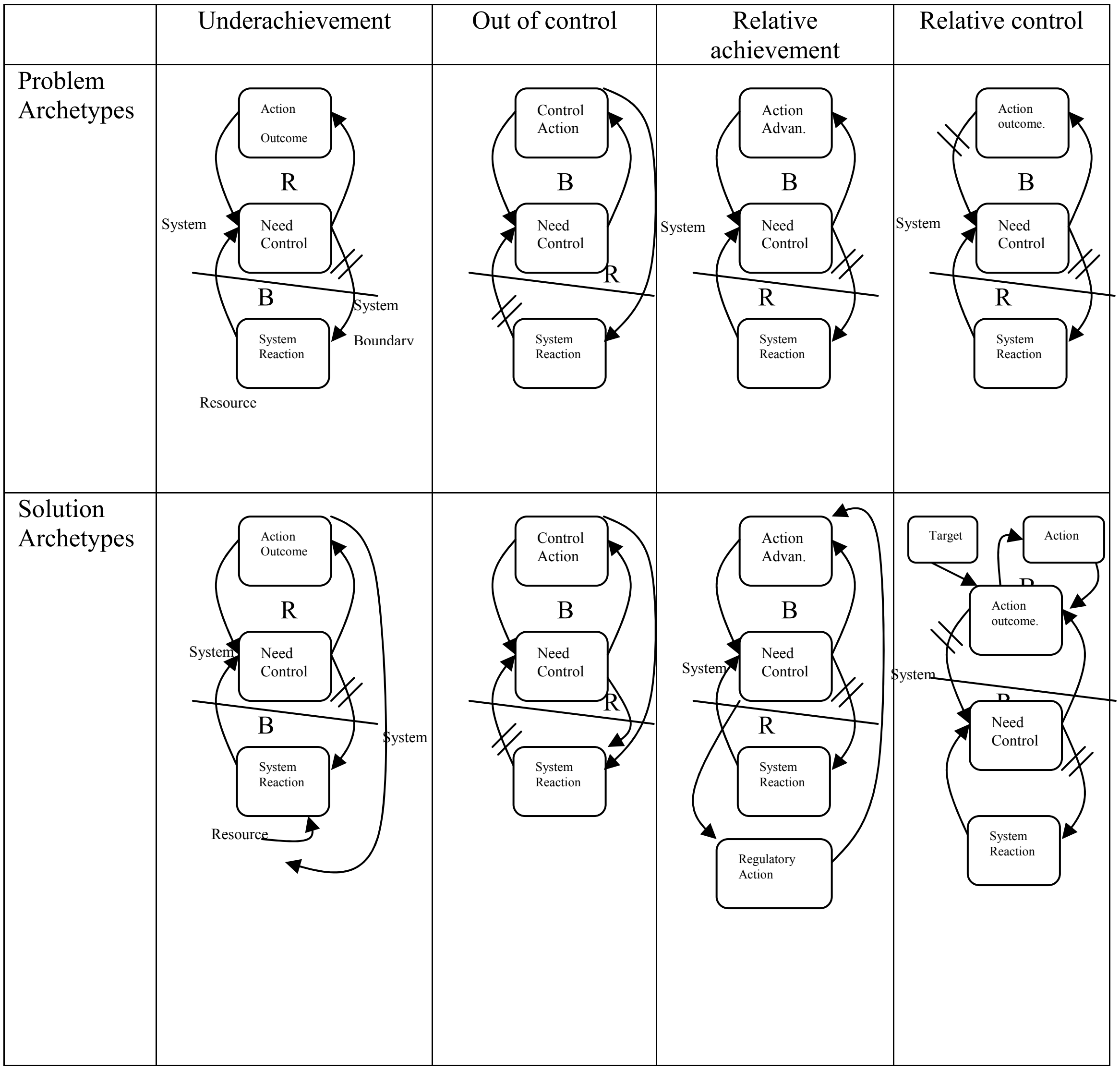


Figure 26: Set of archetypes in system dynamics (Wolstenholme, 2003)

Archetypes are solutions for reducing the complexity of the system size, but those are not enough if we want to test if the SD technique is a good candidate for modeling a network centric scenario. In order to identify strengths and weaknesses of SD models we need additional tools for understanding the behavior of an emergency management organization.

One significant issue for using SD technique in the context of this research is to find out how many feedback loops exist in the structure of an emergency management organization. In Chapter Four we presented a preliminary approach to this problem by mean of the analysis of the vectors *triads* and *dyads*.

Kampmann (2004) showed that in a SD model, the number of feedback loops in a maximally connected graph with *n* variable of state and *p* auxiliary variables reaches the number of $2^{np}(n-1)!$ loops. Furthermore, he argued that there are no general formulas for finding the number of feedback loops for a given system, and he proposed an algorithm to identify all loops in a given graph. (According to the Kampmann formula we tested his outcomes, and they should be considered an estimation of the number of loops in a SD model).

Table 23: Number of loops in a maximally connected system with *n* levels and *p* auxiliary variables (According to Kampmann (2004))

n	*p*			
	0	1	5	10
1	1	2	32	1024
2	3	8	1088	10^6
3	8	34	68704	10^9
4	24	192	10^6	10^{12}
5	89	1458	10^8	10^{16}
10	10^6	10^8	10^{20}	10^{35}

We showed in Chapter Four that an emergency management organization has clear and well defined procedures, and the relationships among its components generate different *configurations* before, during, and after the extreme event.

As those *configurations* are hierarchical *digraphs* which respond to well-defined problems, we might argue that systems for emergency management will have a number of reduced feedback loops, at least in the first period of an extreme event, when the organization can control the effects of the event.

Two examples of the previous statement were showed in the Kobe Earthquake in Japan, and Hurricane Mitch in Central America (Appendix A). In both cases, we hypothesized the existence of initial *configurations* with a reduced number of feedback loops due to the controlled chain of command, but according to the severe evolution of the extreme event, those *"configurations"* were losing their structures and the number of uncontrolled feedback loops increased dramatically. By using graph terminology, the number of graph components also increased, producing a lack of communication, coordination, and situation awareness in the organization. Analyzing the chain of command in Hurricane Mitch, the recurring question "Who is in charge?" is an example of the uncontrolled feedbacks loops that are produced at determined periods in the organization. (See Hurricane Mitch analysis in Appendix A.)

Thus, we conclude that the number loops is relevant for a networked organization, and it might be a good indicator of the emergency management system performance. We argue that the identification of the number of feedback loops is the first step for testing the helpfulness of SD technique in a networked scenario.

Researchers have developed few techniques for understanding the behavior of the feedback loops over time. The most significant of these techniques according to our research are:

- Model analysis – Looks to explain the cause of the oscillations in the feedback loops by using "causal loop diagram" and polarity.

- Loop knockout technique – Useful for studying loop dominance, the modeler disconnects specific loops to analyze what loops have more significance in the system behavior.
- Sensitivity test – Based on variations of parameters, seeks to identify the causes of the system oscillations.
- Eigenvalues analysis– Measures that identify the loops that contribute more to the system behavior.

Because the three first techniques are based on trial and error and they are time consuming, we will concentrate our effort into a mathematical analysis to evaluate the helpfulness of the eigenvalue measures in the study of the network centric scenario.

Eigenvalues and eigenvalues elasticity for evaluating a networked organization

Since SD is a set of nonlinear differential equations, this technique requires us to linearize the equations as a set of linear differential equations. The equation **dX/dt = A X+ b**, represents the SD model under study as a set of linearized matrices with **X** being the state vector, composed by all the variables of states in the system. (Speller, Rabelo and John, 2004).

The eigenvalues of the coefficient matrix **A** determine the expected behavior of the system. This behavior depends on the position of the eigenvalue on the complex plane. Figure 27 shows the six possible behaviors based upon eigenvalues analysis.

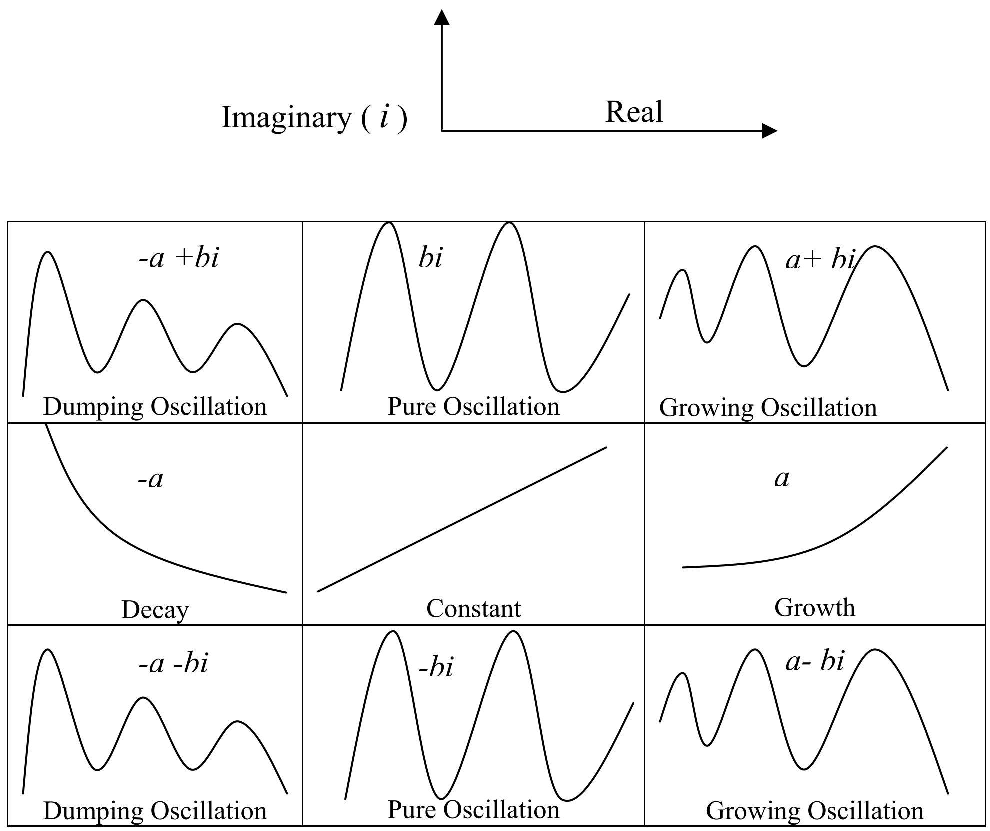


Figure 27: Behavior of a SD model derived from eigenvalue analysis

The real part of the eigenvalue will determine the mode stability. A negative real part will cause decay or goal seeking modes, whereas a positive real eigenvalue will cause exponential growth (positive or negative). A pure imaginary eigenvalue will cause never-damping oscillations.

Complex eigenvalues, which always occur in conjugate pairs of the form a ±bi, where $i^2 = -1$, will identify oscillations and either growth or decay, depending on the sign of its real part; negative implies decay or goal seeking, positive indicates exponential growth (Speller et al. 2006).

The question that arises is: Could SD be a good candidate for simulating the interaction among the nodes in a network centric environment?

Let us answer the question by formulating a small example regarding how local and state authorities could react according to established procedures to a *warning alert* sensor which sends an alarm when a natural extreme event comes out in the jurisdiction of those authorities. (See Figure 28).

The model presents seven variables of states and twelve flows. The reader should note that a SD model of an organization has fewer feedback loops than models used in others fields. There are two reasons that justify this apparent lack of complexity. The first one is the modeling of a hierarchical organization whose adjacency matrix (say digraph) is essentially asymmetric; the second one is the nonexistence of auxiliary variables that alter the correlation between the variables of states (it avoids, in part, the introduction of chaotic behavior in this simple model). We implemented a *pulse* as an in-flow to stand for the external behavior of an extreme event. A *sensor* is a variable of state (*node*) which represents a *warning alert* in a network centric emergency system. The sensor gets data from the *pulse,* and sends a *warning alert* to the *alert* node.

Basically, the *warning alert* is an increment in the rate flow to the next *node*. People in charge of the *alert* node activate the chain of command by sending modified flows to its connected nodes *Situation awareness* and *Local decision maker.* Thus the diffusion information is expanded through the *digraph.*

The *matrix C* and the *digraph* show the connections of the decision makers who are modeled as *variables of states*. The main assumption in the model is while more flows of data arrive to the *nodes, variables of states* transmit data with more intensity to others *nodes* (regulated by the flows). Thus, we use the *variables of states* as control of the internal nodes' *behavior*. By using this technique, we are constrained to model only one type of flow among the nodes, and if another type of flows is required, then we need another SD model.

$$C=\begin{pmatrix} 0&1&0&0&0&0&0\\ 0&0&1&0&1&0&0\\ 0&1&0&1&1&0&0\\ 0&0&0&0&1&0&1\\ 0&1&0&1&0&1&1\\ 0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0 \end{pmatrix}$$

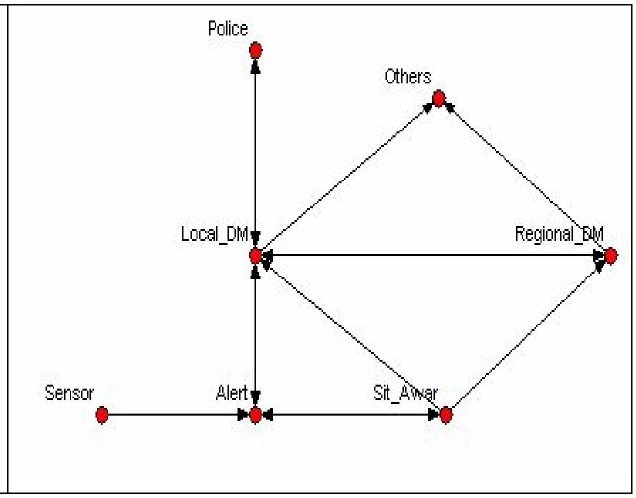


Figure 28: Adjacency matrix for a warning alert scenario

The digraph, in Figure 28, contains seven nodes and thirteen connections. The matrix C was used for collecting statistics information in regard to the sub-graphs produced by the dyad census, in Table 24. There are four *mutual* dyads and five *asymmetric* flows; also the census shows that twelve *null* dyads are produced in the emergency system.

Figure 29 shows a sketch of the SD model which represents the adjacency matrix C. The blue arrow represent the feedback loops shown in the matrix C. A triad census was conducted for collecting the triads that arises from the SD model Table 25.

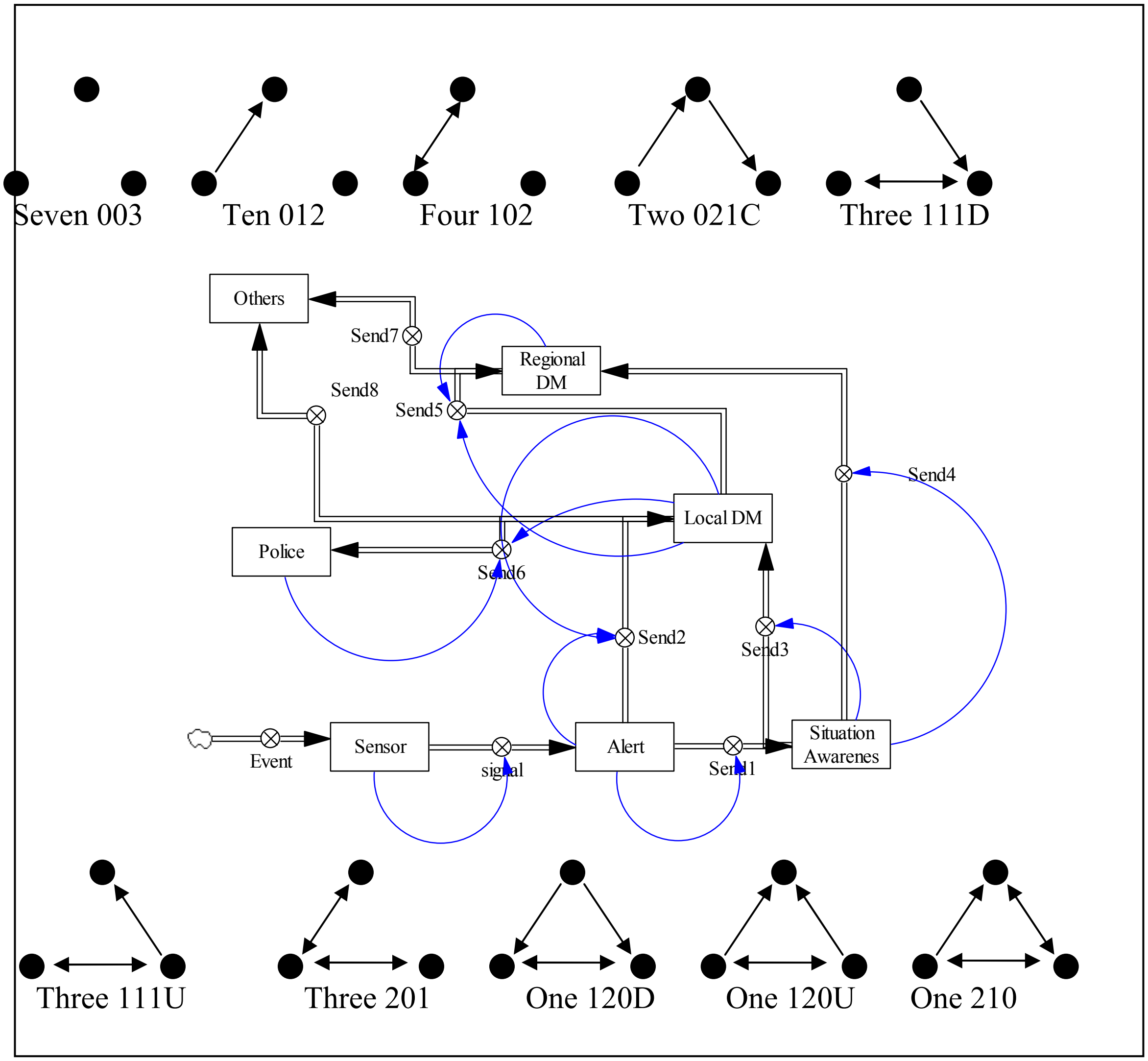


Figure 29: Triad census performed in a SD model with seven stocks (SD model was implemented in Vensim software and digraph analysis in Netminer software)

In Figure 29 there is a dominance of the *triad 003* and *012*, the former points out a null connection among seven triads and the latter shows asymmetric flows characteristic of the hierarchy organizations without feedbacks.

Table 24: Dyads census

Nodes: 7 Arcs: 13	Observed	Expected
Number of Mutual Dyads	4	3.116
Number of Asymmetric Dyads	5	5.884
Number of Nulls Dyads	12	12

Table 25: Triads census

Nodes: 7 Arcs: 13	Observed	Expected	St Dev.	Std. Err.	Variance
003	7	6.42	1.02	0.032	1.04
012	10	9.42	2.25	0.071	5.09
102	4	2.11	1.34	0.042	1.79
021D	0	0.74	0.74	0.024	0.56
021U	0	1.02	0.66	0.021	0.43
021C	2	3.66	0.87	0.028	0.76
111D	3	2.94	0.89	0.028	0.80
111U	3	3.15	0.74	0.024	0.56
030T	0	0.96	0.75	0.024	0.56
030C	0	0.14	0.35	0.011	0.12
201	3	1.17	1.04	0.033	1.09
120D	1	0.25	0.44	0.014	0.20
120U	1	0.33	0.49	0.016	0.24
120C	0	1.12	0.76	0.024	0.58
210	1	1.43	0.57	0.018	0.33
300	0	0.013	0.11	0.004	0.13

Four triads show a *mutual* relationship, and since that the system is composed by only seven nodes, we might suggest that the configuration presents a high grade of feedback among its components. It is consistent with the feedbacks loops produced by the four dyads found in the dyads census in Table 24.

If we generate a random digraph with seven nodes and thirteen connections, we could expect the number of type of dyads and triads shown in Tables 24 and 25. By now, we do not compare the observed with the expected columns in both tables, because of the reduced number of nodes in the digraph. Additional conclusions we can get by analyzing the matrix C with the *"one mode"* social network measures showed in Chapter Four.

By performing feedback loops analysis, we collected the outcomes in three nodes: *Local Decision Maker, Alert and Situation Awareness*. Table 26 shows the feedbacks loops of length 1 to 7.

Table 26: Feedbacks loops in the nodes local DM, alert and situation awareness (Loops generated by using Vensim software)

Local DM	Alert	Situation Awareness
Loop Number 1 of length 1 Local DM Send6 Loop Number 2 of length 1 Local DM Send5 Loop Number 3 of length 1 Local DM Send2 Loop Number 4 of length 5 Local DM Send2 Alert Send1 Situation Awareness Send3 Loop Number 5 of length 7 Local DM Send2 Alert Send1 Situation Awareness Send4 Regional DM Send5	Loop Number 1 of length 1 Alert Send2 Loop Number 2 of length 1 Alert Send1 Loop Number 3 of length 5 Alert Send1 Situation Awareness Send3 Local DM Send2 Loop Number 4 of length 7 Alert Send1 Situation Awareness Send4 Regional DM Send5 Local DM Send2	Loop Number 1 of length 1 Situation Awareness Send4 Loop Number 2 of length 1 Situation Awareness Send3 Loop Number 3 of length 5 Situation Awareness Send3 Local DM Send2 Alert Send1 Loop Number 4 of length 7 Situation Awareness Send4 Regional DM Send5 Local DM Send2 Alert Send1

A complementary insight we obtain from Table 26, since that triad and dyads census provided some hints in regard to static behavior of the system, now we find out the exact number of the direct and indirect causal relationships that influence the final behavior of each node. Clearly those feedbacks loops are measures of the complexity of the system in each critical point. For instance the node *Alert* has four loops whose lengths are; 1, 1, 5, and 7.

The fourth loop involves four flows and three variables of states, and it confirms the presence of one triad 210 (see Figure 29) obtained in the digraph analysis.

Figure 30 shows the behavior of four nodes in the system, the simulation was implemented in a timeframe of 100 units of time. Tables 27 and 28 show the dynamic matrix A, at the periods 10 and 90. The reader should note as matrix A changes its values and its eigenvalues in time according to the equation $Ax = \lambda x$, where λ is an eigenvalue of the matrix A, and x is its associated vector.

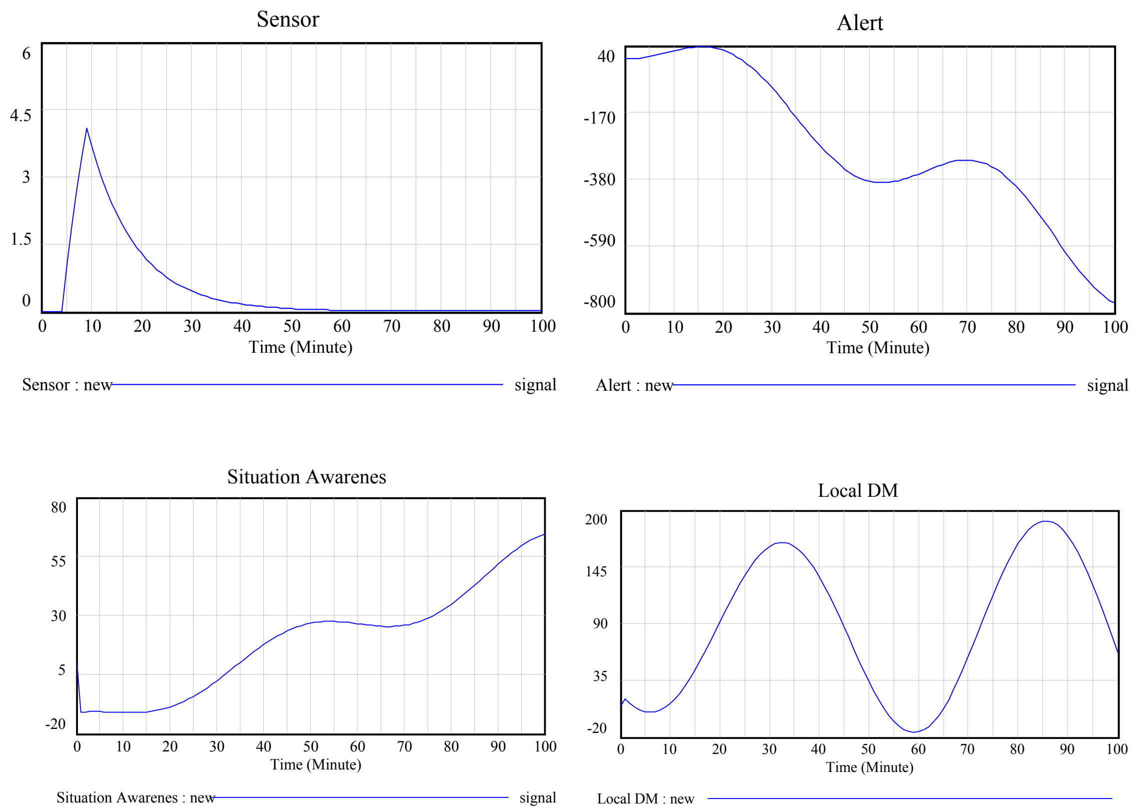


Figure 30: Behavior of node in the warning alert system

In Figure 30 the graph *sensor* shows the behavior of the node which only is driven by the pulse generated by the extreme event, at time 4. Notice that this graph is consistent with the eigenvalue -*0.00298 + 0.11864i* shown in Table 27, Table 28 and Figure 27. Basically the damping oscillation decays constantly at the period t=10 and t=90.

The graph *Alert* shows a decay behavior, which also is consistent with its eigenvalue -0.1 + 0i shown in Table 27, Table 28 and Figure 27.

The situation awareness shows a goal seeking behavior at the period t=10 and t=90. The eigenvalues do not change in the time.

The graph *Local DM* shows an oscillatory behavior which corresponds to permanent changes of sign in the real and imaginary parts of its eigenvalue (See Table 27 and 28. Data was obtained using Vensim Software, Analyzt software and Netminer software.)

The feedback loops in Table 26 show that the behavior of either one or several variables could influence the behavior of others variables. In order to determine the magnitude of the influence, we calculate the elasticities of the eigenvalues. Basically, this index enables us to identify the loops that govern the behavior of a selected variable.

Selecting as variable the node *Alert* (shadow value), we identified the intensity of the relation that exists between the feedback loops and the node *Alert*. At the times t=10 and t=90 we can see that the *Sensor* node is the main direct causal for the decay behavior of the node *Alert.*

Table 27: Dynamic matrix A, time=10: Eigenvalues and eigenvalues elasticities

Eigenvalue Analysis Time = 10 Regional DM- Sensor- Situation Awareness- Others- Police- Local DM- Alert								
Dynamic Matrix A							Eigenvalues	
0.1	0.0	0.5	0.0	0.0	0.1	0.0	-0.99405	velocity 0i
0.0	-0.1	0 .0	0.0	0.0	0.0	0.0	-0.00298	velocity 0.11864i
0.0	0.0	-1	0.0	0.0	0.0	-0.1	-0.00298	velocity -11864i
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	velocity 0i
0.0	0.0	0.0	0.0	0.1	0.1	0.0	-3.97e-012	velocity 5.74e-007i
-0.1	0.0	0.5	0.0	-0.1	-0.1	0.1	-3.97e-012	velocity 5.74e-007i
0 .0	0.1	0.0	0.0	0.0	-0.1	2.31E-11	-0.1	velocity 0i
Loop Elasticities								
Sensor →→Sensor							-0.99999	velocity NaN
Regional DM→→Regional DM							4.18458e-005	velocity NaN
Situation Awareness →Situation Awareness							-2.20177e-005	velocity NaN
Police →→Local DM→ Police							1.89066e-005	velocity NaN

Table 28: Dynamic matrix A, time=90: Eigenvalues and eigenvalues elasticities

Eigen value Analysis Time = 90 Regional DM- Sensor- Situation Awareness- Others- Police- Local DM- Alert	
Dynamic Matrix A	Eigen values
0.1 0.0 0.5 0.0 0.0 0.1 0.0	-0.99405 velocity 0i
0.0 -0.1 0.0 0.0 0.0 0.0 0.0	-0.00298 velocity 0.11864i
0.0 0.0 -1 0.0 0.0 0.0 -0.1	-0.00298 velocity -11864i
0.0 0.0 0.0 0.0 0.0 0.0 0.0	0.1 velocity 0i
0.0 0.0 0.0 0.0 0.1 0.1 0.0	7.4926e-007 velocity 0i
-0.1 0.0 0.5 0.0 -0.1 -0.1 0.1	-7.5061e-007 velocity 0i
0.0 0.09 0.0 0.0 0.0 -0.1 -1.19E-11	-0.1 velocity 0i

Loop Elasticities		
Sensor →→Sensor	-1.0000	velocity NaN
Situation Awareness →Situation Awareness	-4.29693e-005	velocity NaN
Police →→ Police	-3.15856e-005	velocity NaN
Local DM→→Local DM	2.04404e-005	velocity NaN

Although SD technique is only based on the connection of three elements – inflows, outflows and variable of state – all connected by feedback loops, the non linearity that arises from the interaction of those variables is hard to control, especially in a model with more than three variables of state.

By using eigenvalues, we demonstrated the stability of an SD model can be controlled and significant conclusions can be obtained from its analysis.

On the other hand, if the feedback loops are an obstacle for evaluating the accuracy of the performance of an ICS, we can reduce the complexity by using the ego-net concept from Chapter Four, thus we might reduce the number of *nodes* and concentrate our effort over a *sub-graph* of the whole system.

Discrete simulation: A network centric approach

Traditionally discrete simulation techniques have been used from a *discrete event* perspective such as manufacturing systems, services lines, business and supply chains. Whereas all those models are regulated by an *event scheduling* mechanism, little attention has been given to the combination of others discrete approaches such as *petri net, agent based, finite machine, and state transition*. This is likely because there exists a number of commercial packages for implementing *discrete event simulation*.

In the context of a network centric scenario, we will analyze the synergy that arises from the interaction of two discrete simulation techniques, *discrete event* and *state transition,* making emphasis in the advantages that present the combination of both techniques for modeling an emergency management organization in a networked scenario. Thus, for a network centric analysis, a comprehensive definition of *discrete simulation* is: "Modeling of a system over the time, where the *state of the variables* change according to either fixed mechanisms or by controlled algorithms over the processes."

Fixed mechanism makes reference to the two historically main approaches for advancing the simulation clock: *next-event time* and *fixed-increment time advance* (Law & Kelton, 2000), and as extended literature exists in *discrete event simulation,* we will concentrate our discussion primarily on *state machine* discrete approach. We will demonstrate part of our methodology for fitting a discrete simulation based on *state transition* with a standard *discrete event* approach, and we will show how both implementations might be used in a networked scenario.

A model based upon *state transition* has four components (adapted and modified from Mosterman, Biswas and Sztipanovits, 1998):

- $I= \{\mu_o, \ldots\ldots\ \mu_k\}$ the set of states describing operational modes of the system.

- $\sum=\{\sigma_o, \ldots\ldots \sigma_k\}$, the set of events that can cause state transitions. Events are generated by dynamic process, the closed-loop controller, and by external, open-loop control signals, i.e., $\sum= \sum p \; x \sum c \; x \sum x.: I \; x \sum \rightarrow I$, a discrete state-transition function that defines the new mode after an event occurs.
- $C= \{ I_k \ldots\ldots I_k \}$ represent a community of set of states defined in the context of a network centric scenario.

We characterize the state μi as the set of values shown by the variables and parameters of a system during a certain period of time. If we define a discrete event process over time as σ*i,* then *the state* μi always could describe either the entire process or part of σ*i.*

On the other hand, we could use σ*i* for driving the set of events $\sum$. Thus the discrete event model will determine when the discrete function ϕ triggers the transition toward a new μ_k. The function ϕ is transitive and reflexive; it might transfer the control from one state to another or back to the original state. The final behavior of the system arises from the combination of all the states of the system.

The implementation of a combined *discrete event* and *state transition* model presents multiple advantages for understanding the strengths and weaknesses of an emergency management organization, especially if data is available to simulate the interactions between *nodes* and to drive the scenarios that should face an ICS.

Using unified modeling language (UML) definitions, we will describe four types of *state transition*s and we propose a fifth state named *community of states* which fits well for implementing our proposed hybrid methodology.

- Sub-state: A state which resides within another state.
- Sequential states: A chronological succession of states that occur one after the other.

- Concurrent states: States executed at the same time.
- Composite states: A state composed of other concurrent or sequential states.
- Community of states: A set of states located in either different composite states or objects for which signals are their main mechanisms of communication.

The *community of states* enables the implementation of a concurrent behavior in more than one composite state, allowing the generation of a set of communities; thus $C = \{ I_o, \ldots I_k \}$ is the community of states describing the whole set of operational modes of the system.

We propose a *state transition* technique for governing the external events which should produce a chain of reactions on the whole emergency management organization according to how it is regulated in the EOP. The *community of states transition* should show the *states space* with the algorithms, events, and transitions.

For instance, the Figure 31 shows two classes with two composite states of transition each one for controlling the chain of command and decision making processes.

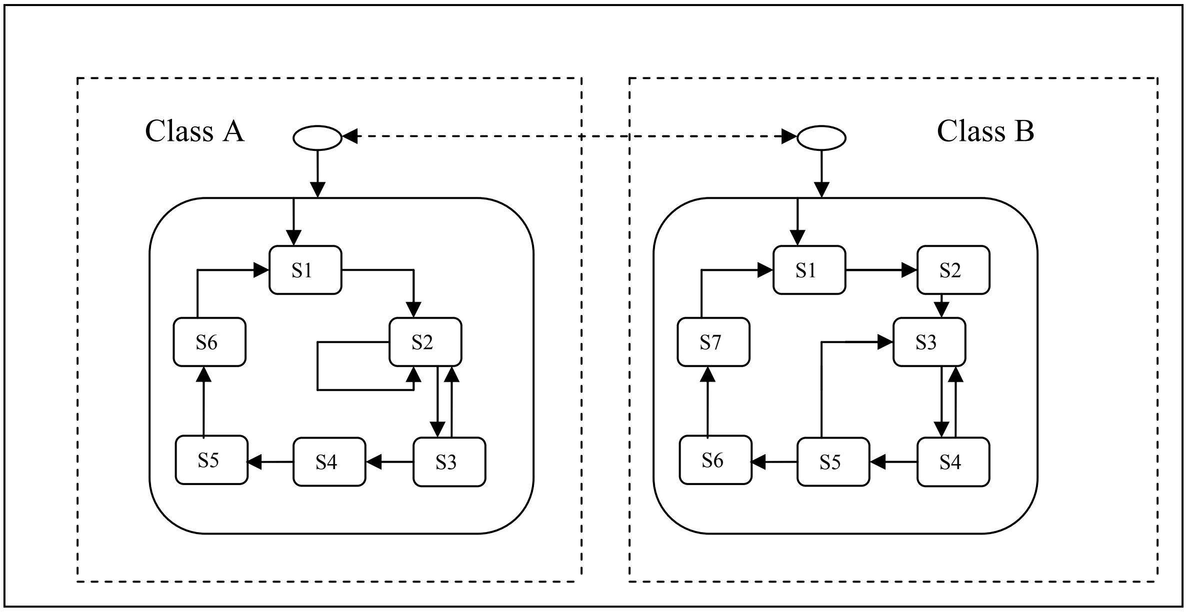


Figure 31: Community of states defined for a network centric scenario

The *community of state transition* is well situated as a control mechanism that the modeler can use for testing different components of the whole system. The succession of events over time could be regulated by using either random or deterministic variables for controlling the transitions, events, and actions.

Integrating system dynamics and discrete event simulation

So far, we have focused our methodology on continuous and discrete variables separately by using SD, DES, and *state transition* simulation techniques. Now we will concentrate our effort on identifying comprehensive mechanisms for modeling more complex behaviors putting together continuous and discrete variables.

The behavior of an emergency management organization depicts both discrete and continuous variables; the former might be resources, entities, process time, queuing messages, and activation alarms, and the latter might be the effect of stress on the team, time for accomplishing a task, and evolution of a physical event.

By using both techniques we have to distinguish between two different modeling approaches:

- Interactions of models
- Interactions of variables

Interaction of models means that one part of the system was modeled by using SD technique and the other part by using DES technique, and both models interact through a discrete interface.

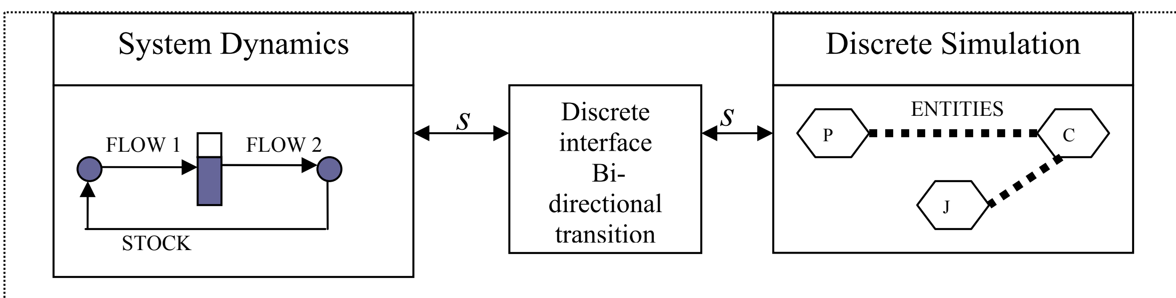


Figure 32: Interaction of models in hybrid simulation approach

Figure 32 shows the two models; a continuous with a feedback loop based on SD, and a process flow, in which the entities follow a programmed sequence based on DES. Both models interact only through a discrete *state transition* interface that manages the changes of the dynamic parameters. The configuration requires the use of sensors and signals for detecting when selected variables from both simulation techniques cross specific thresholds.

Figure 33 shows that the second modeling approach, named interactions of variables, implies that there exists only one model implemented by means of two simulation techniques. Thus,   either the variables of the SD model could be dynamics parameters of the DES model or the variables of the DES model, such as number of entities in the queue or resources utilization could be dynamics parameters that modify the behavior of the variables of state (level) in a SD model.

From the interaction of variables arises the concept of *dynamic simulation,* since the parameters of the processes (DES) and flows (SD) change over time.

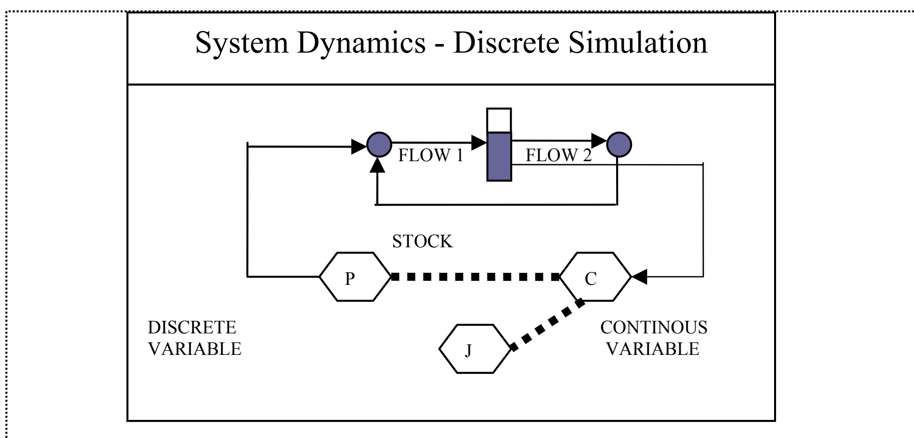


Figure 33: Interaction of variables in a hybrid simulation approach

By using the two previous approaches, the modeler of a network centric environment has the chance to capture six types of behavior as is shown in Figure 34.

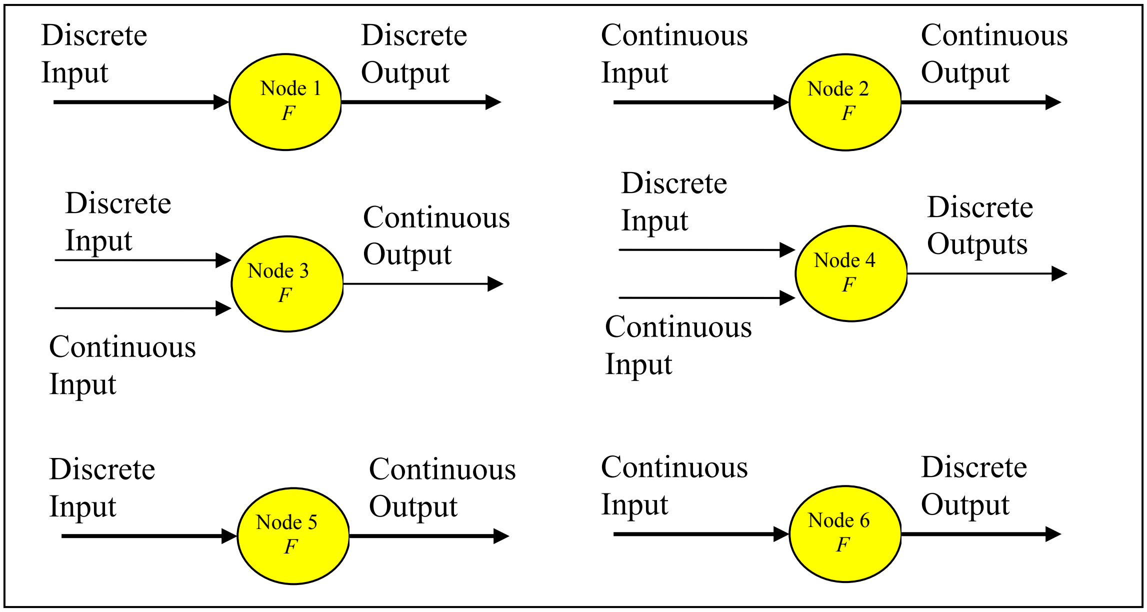


Figure 34: Variables' behaviors according to inputs and outputs mechanisms

Since an input to the *Node 1* applies the function *F* and produces a discrete output, this could be the case of a classical discrete event simulation.

In contrast, if *Node 2* is a *state variable*, then it seizes the flows and applies the function *F* to the in-flows (for those familiar with SD, *F* could be an *information delay*) and it releases the *out-flows* according to a fixed *rate.*

Node 5 shows the effect of discrete variables which produce a continuous behavior over the node. An example is a discrete extreme event such as an explosion that generates, by means of a function *F,* stress over the population; the effect of this stress is a continuous variable.

Node 6 receives continuous input and, after applying *F,* releases discrete outputs. A clear example of this kind of behavior is the effect of the fatigue over the number of tasks carried out by a team. It is assumed that as the team works more hours continually, the rate at which it completes tasks will decrease.

Nodes 3 and 4 are combinations of the processes described for the other four nodes.

Conceptual model of a network centric decision making scenario

After discussing how to combine the main simulation techniques available for modeling continuous and discrete processes, we define a conceptual model of the organizational structure and the network centric environment in which it performs its tasks.

By means of a conceptual model design, we specify three main sets of features of a modeled system:

- Essential components of the organization structure.
- The relationships of the nodes and their position in the structure.
- The kinds of changes in either the environment or the emergency organization that affect the functioning of the complete structure.

In order to present the design logically and according to the current “mental model” that the people and community have of an emergency management organization, the conceptual model was designed following the structure of a set of interconnected graphs. The model captures the essential elements of an ICS which was defined as “the combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure” (NIMS, 2004). Those essential elements are:

- Structure representation of the emergency management organization based on an ICS.
- Dynamic interaction into the elements of an ICS.
- Identification of measures of performance and vulnerabilities in the organization structure.

- Evolution of the configuration over time by the effect of new events and interruption of the *dyads flows.*
- Representation of resources available.
- Representation of the internal structure of the elements in the networked organization.
- The communication between the elements considers diffusion of information rate.

Making use of the level of aggregation defined in Chapter Four, each element that plays a critical role in the structure of an ICS is modeled as a node, allowing a high level of granularity.

Besides providing a model that aligns the mental models that the modelers and decision makers have of a networked emergency organization, the conceptual model enabled us to create fixed mechanisms for merging simulation technique with graph structure. Thus the static *dyad* and *triad* relationships of a *digraph* can evolve toward a simulated model that contains the configuration of an ICS at local, state, and federal levels.

We conceptualized the model in five steps which represent the evolution of the processes of decision making in an ICS. See Figure 35.

Step 1 captures the organization layout and the adjacency matrix ***N*** of the *digraph* associated with the organization structure. Figure 35 (shadow area) shows the asymmetric relationships among the *nodes* that correspond to the hierarchy's emergency organization.

Step 2 corresponds to the definition of the set of discrete and/or continuous events that begin the activation of the system by means of signals. A sensor should transfer the signal to the set of nodes in the organization. The signal is a function of the type of event and how it evolves over time.

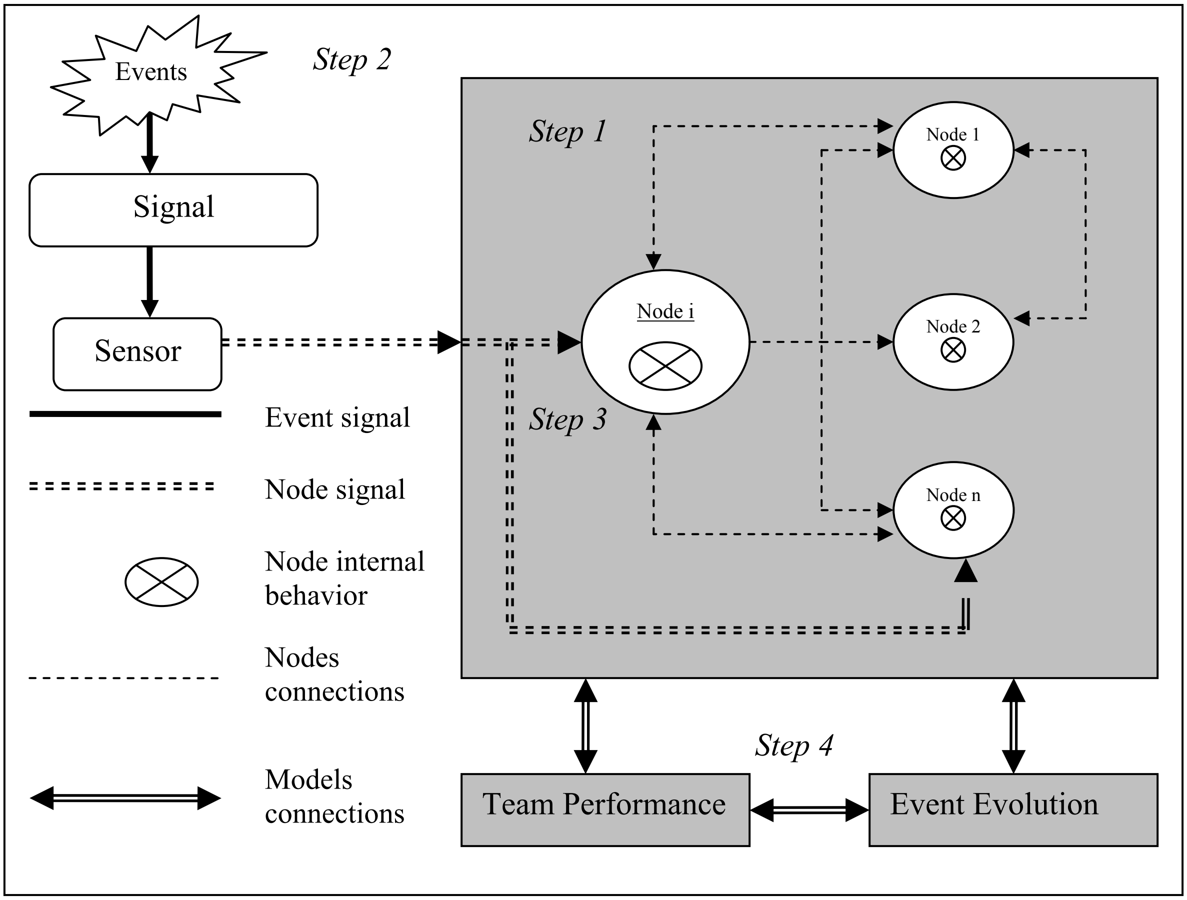


Figure 35: Conceptual model

Step 3 must consider the representation of the internal structure of the *nodes* based upon pieces of information received, processed, and transferred to other nodes. The complexity of the internal structure of the *nodes* is a function of the role and position that the *nodes* have in the *digraph*. Thus *nodes* with similar roles like *task forces* should have similar compositions, but the parameters that govern their internal structure will be different. For example, a small team of fire and rescue personnel at a local level is different from a military engineering company specialized in rescue and construction, but their organizational processes are similar.

In step 4, the methodology contains the exogenous and endogenous variables, those that affect the organization performance. In agreement with the lesson learned from the five case studies, we have considered two types of models that influence the organization; team performance and the evolution of the extreme event.

Step 5 considers the dynamic interaction among the *nodes*. This step is linked with the analysis of the longitudinal network pointed out in the previous chapter. Since there exist *dyads* that modify their behavior in time, the model captures those changes in fixed times to apply longitudinal network analysis. This step is highly dependent on the data available in the database of the organization. Those changes will be shown in the adjacency matrix ***N*** and as consequence will produce changes in the *digraph.*

Finally, Step 6 conceptualizes the transmission of different types of data and resources between of the nodes.

Operational model of a network centric scenario

After defining a conceptual model, we present a blueprint of our vision of a networked scenario in which an emergency management organization performs its tasks according to well documented alarms and procedures contained in the ICS and EOP. This framework provides mechanisms for capturing, sharing, and communicating the essential objects and interactions of a given *configuration* and its surrounding scenario.

Early, we defined the concept of a *digraph* for studying the mathematical structure of an organization and since the graphs enable a *one-to-one* modeling of the nodes components and the subsequent interactions that arise from the system, our approach combines these characteristics with an object oriented (OO) design and language implementation of an emergency management system.

By taking the best of these two worlds (graph and OO) it is possible to analyze complex networked organizations (hundreds of nodes with thousands of connections) by defining only a few pattern behaviors of the nodes.

Someone could argue that that functionality has been already performed by an exhaustive *digraph analysis,* but this is incorrect because that *digraph analysis* examines the isomorphic relationships from a static perspective only. Here we additionally incorporate the analysis of the dynamics flows performed by the nodes and suggest the necessity of defining internal nodes' behaviors and external objects that affect the performance of an organization studied as a *digraph.*

For instance under an OO design we propose a *decision maker* behavior which represents the position and role of *n* nodes in the *digraph*. Thus, the *decision maker* is a class of the model, and the objects "*decision maker_1, decision maker_2…decision maker_n"* are instances of that class. By using this approach, a modeler might model different roles such as people in charge of a federal agency, an incident commander, or a city mayor in a county only changing the parameters of the named class.

An object oriented approach provides us similar arguments by defining several subclasses that inherit the behavior of a super class. In this way, we are dealing with the complexity for providing behavior to the multiple nodes in the adjacency matrix.

The starting point for combining a *digraph* approach with OO modeling is defined by the operational model depicted in Figure 36. We portray an emergency management organization in three levels – federal, state, and local – and as consequence three clusters arise from the organizational structure (Usually an adjacency matrix does not allow identifying *clusters nodes*, *ego-net,* or *component digraph* easily, and algorithms and statistical analysis will be required). The city and state levels have sensors for detecting automatically the signals that might send an extreme event; only in this case the *dyads'* relationship between two *nodes* is always asymmetric. In all others cases the three dyadic isomorphism types can be found in the organization.

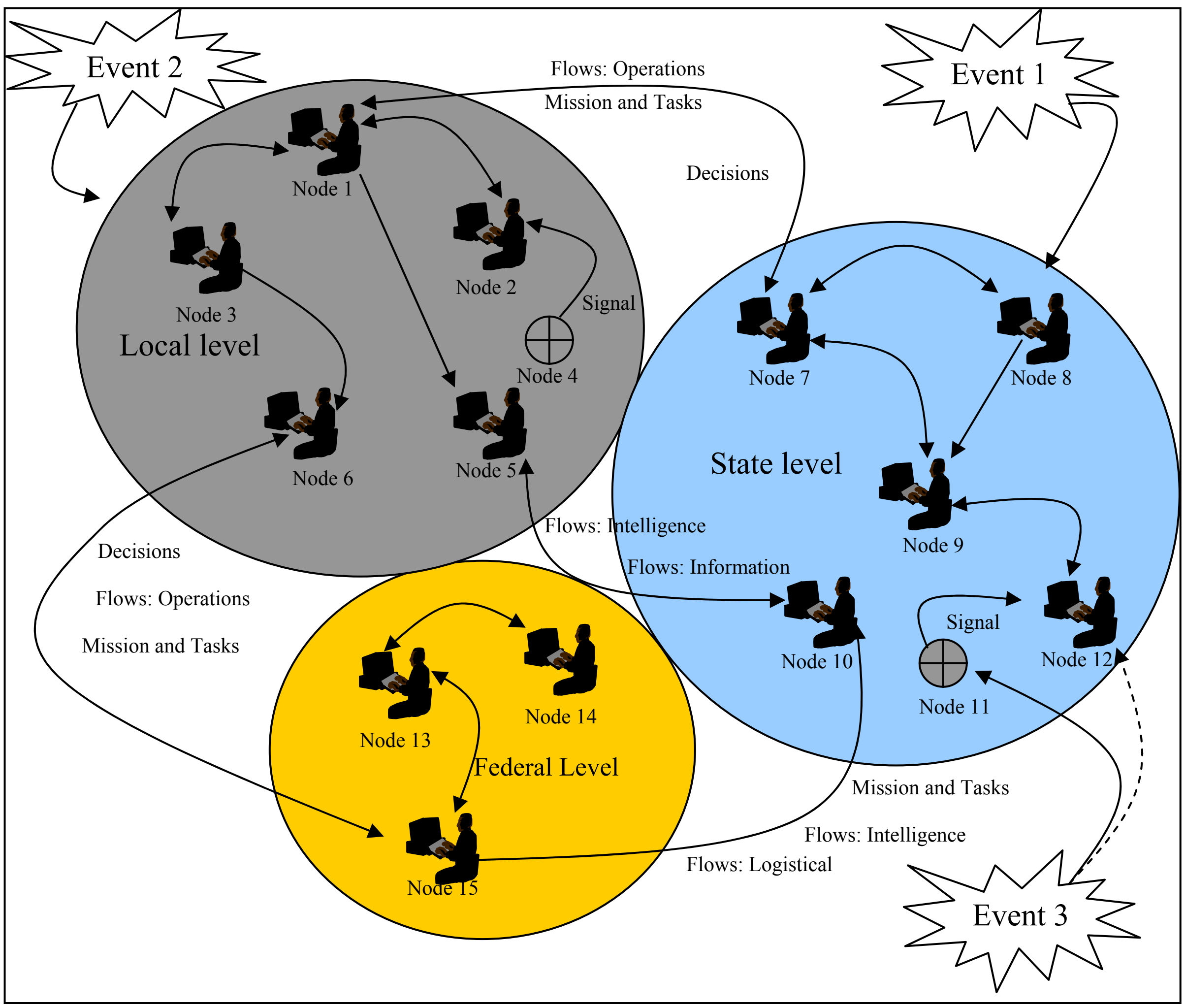


Figure 36: Operational model based on the interactions among dyads of the digraph

Based upon the five disaster cases analyzed in Chapter Three, we suggest that the emergency organization have three different ways for realizing that a critical event arose (See in Figure 36 how events 1, 2, and 3 arrive in the organizational structure):

- By a node that initially takes knowledge of the critical event and transfers the information to other nodes of the organization (e.g. a hospital director that detects in his facility an illness which might evolve into a pandemic).
- By a set of nodes that simultaneously take knowledge of a critical event and transfer the information to other nodes (e.g. local authorities that simultaneously see a tanker truck fire on the local TV news).
- By the whole organization that simultaneously takes knowledge of the critical event (e.g. an earthquake which affects an entire country).

The dissemination of the data and resources in the networked organization is complex due to the multiple *nodes* that take part in the incident procedures and the different types of data that the *dyads* transfer between them.

According to the structured and non-structured data transferred in real command and control systems and in simulated training systems (e.g. constructive simulations), we propose a classification for modeling and simulating the data transferred between the *dyads* of an *organization digraph* (Figure 37).

- *Alarms.* Standard procedures which are known by all nodes of the organization, provides the preliminary data for reacting to an extreme event.
- *Collaborative communication*. Several non structured messages transferred by email, face to face, telephone, radio, and other electronic devices. Must always be classified according to their purpose, such as logistical, intelligence, operational, personnel, etc.

- *Decisions.* Given a critical event, a decision maker performs milestones named *decisions,* carried out after getting early *situation awareness* by means of collaborative tools.
- *Missions.* Given a critical situation, it defines the tasks, units, goal, timeframe, and resources. These are mandatory messages format which are recorded in the database.
- *Tasks.* Activities which must be accomplished by a task force; they are consequences of the missions and still recorded as message format in the database.
- *Resources.* Physical equipment, supplies, or personnel required for carrying out a task. They are defined in the mission to support the way a task is achieved.

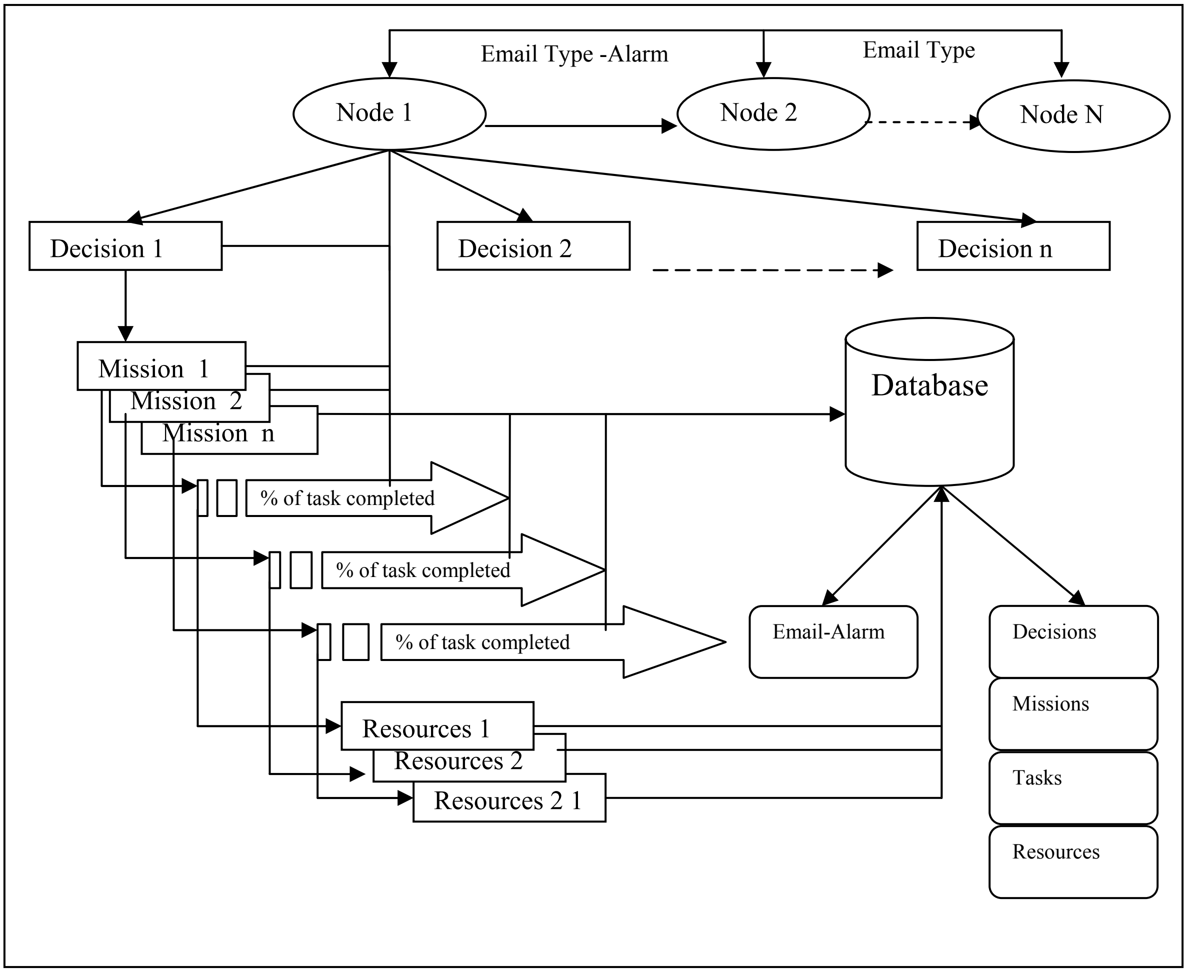


Figure 37: Summarized schema of the data and resources transferred among the nodes in a command and control emergency system

CHAPTER SIX: HYBRID MODEL IMPLEMENTATION AND EXPERIMENTAL RESULTS

Introduction

In Chapter Three we suggested that any emergency organization performs its tasks over three domains: physical, cognitive and informational. Thus this methodology proposes to incorporate those domains over a simulated environment by using graph structure, discrete event, states of transition, and system dynamics techniques.

In order to demonstrate the last part of the methodology process, we implemented a simulated model based upon the operational model exposed in Chapter Five.
Based on the ICS *digraph* (Appendix B), we define a hypothetical structure of an ICS with thirty-seven nodes which are implemented at three levels: federal, state, and local.

Through the first part of this chapter we explain the continuous and discrete components of the model that enables us to represent the internal and external behavior of the ICS *digraph*. In the second part of this chapter and according to the graph classification defined in Chapter Four, two sets of measures are used to explain the structure of the *digraph* that represents a networked emergency organization. These sets of measure are *node level analysis*, and *sub-set and network level analysis.*

Finally in the third part of this chapter, we develop an experimental analysis of the discrete interactions of the thirty-seven nodes that encompass the *digraph* and combine those results with those obtained from the social network analysis.

<u>Model implementation</u>

An overview of the proposed model is shown in Figure 38. Given that the model is a *one-to-one* mapping of the hypothetical emergency structure, the thirty-seven nodes are represented as thirty-seven objects in the model.

In order to provide one common interface of the whole scenario to other possible digraph configurations, we encapsulated the *digraph* and its surrounding environment in a super-class named *main1*.

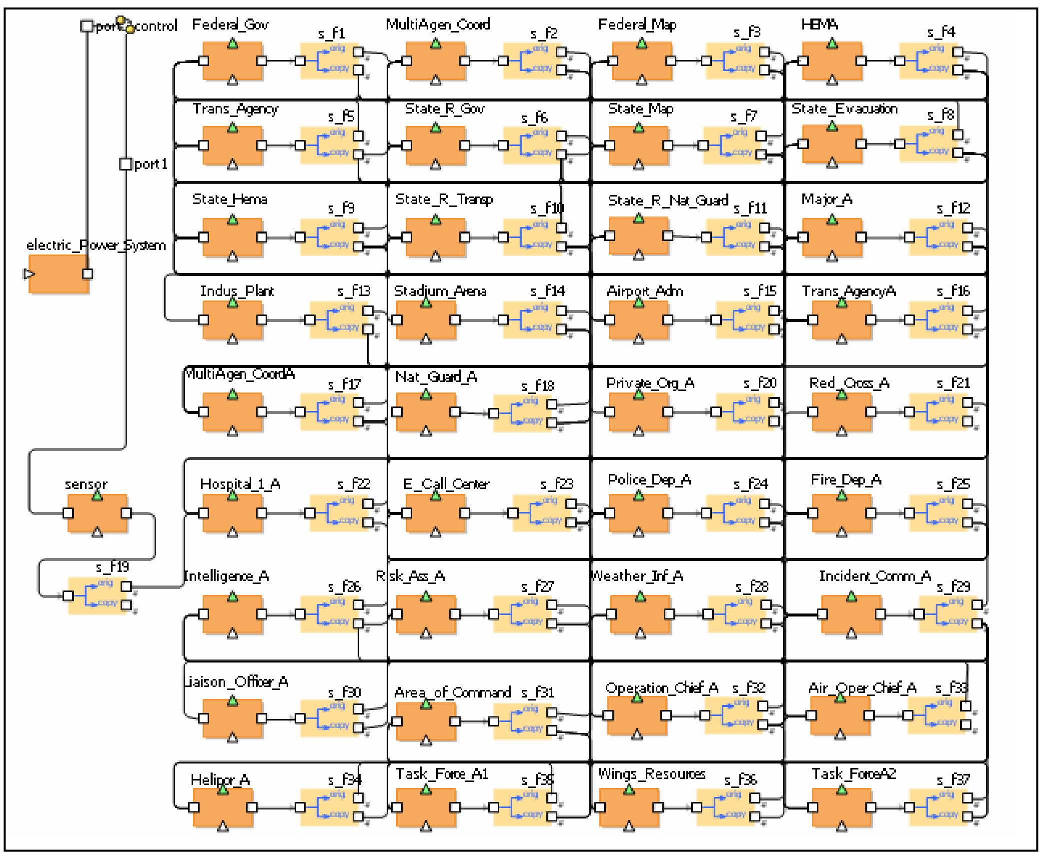


Figure 38: Encapsulated objects for representing the three domains in the *digraph*

The class *Electric_power_system* represents a portion of the critical infrastructure in the physical domain. The object *electric_power_system* is an instance of this class and contains the SD model of a power grid that feeds two big cities.

In Chapter Five we showed how different simulation techniques could combine to produce a desired behavior. In this case, the power grid is a continuous network that is constantly monitored by a control system. When the electrical power either fails or reaches a critical level, a control system modeled as a *state transition* object sends a signal to an object named *external_control*, which is a set of *states transition*. Thus we are applying the defined concept of *community of states*. Figure 39 shows the SD class and the encapsulated *state transitions.*

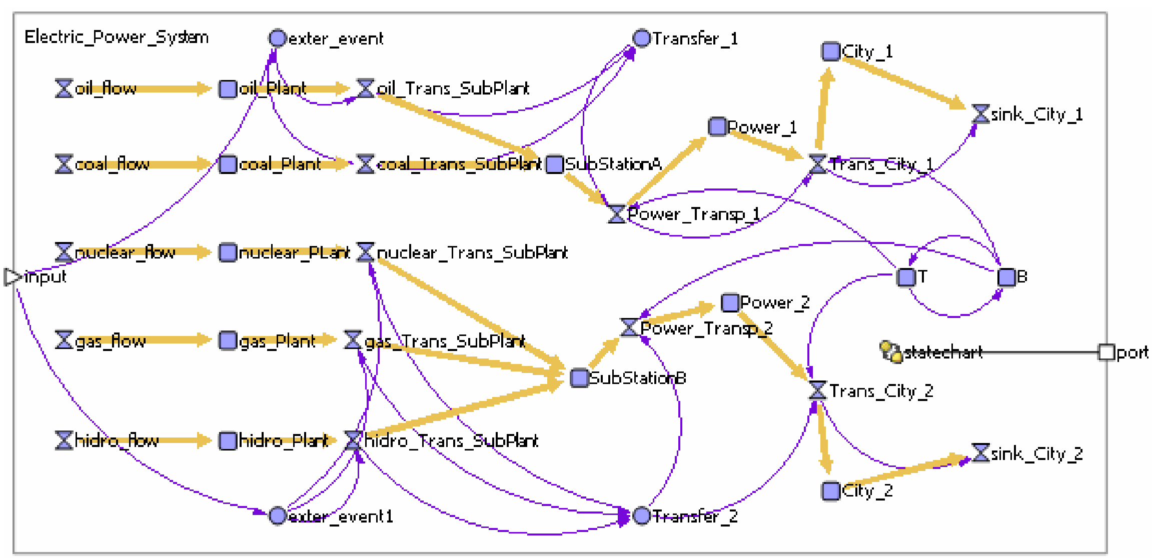


Figure 39: System dynamics model that feeds others simulation techniques

The SD model has five state variables, which are levels of accumulation of electricity produced by five sources named oil, coal, nuclear, gas, and hydro plants. A set of networks formed by the interactions of the states variables (squares), inflow (valves), out flow (valve), and auxiliaries' variables (circles) show the causal dependency in the complete system.

Four state variables are used for representing the transference nodes that carry the electricity toward the cities, and finally two variables of states called City_1 and City_2 stand for the accumulator levels required for supplying both cities.

The *power grid model* represents a type of extreme event that might be useful for producing input to test the chain of command of the *digraph.* Because of the OO design of the whole model, the implementation remains open to incorporation of other classes which might represent different events.

In the context of a networked scenario, we suggest two approaches for relating a SD model with another simulation paradigm. The first is by means of a set of continuous variables that are shown as interfaces of the external model. Thus, other objects interact with those variable interfaces according to pre-established rules. The second approach is by means of a *state transition* interface which was used in the SD model shown in Figure 29.

The best approach will depend on the type of system that the modeler is attempting to build. According to our methodology for simulating a networked scenario with three domains, we suggest connecting a SD model with the state of transition technique, because in this way the modeler can control the whole behavior of the model by means of conditions specified for triggering transitions to different states.

According to the operational model, the extreme event will evolve as a set of differential equations where it is possible to distinguish three specific timeframes:

- The period previous to when the event reaches its threshold, which is named ***T-***.
- The exact time in which the event reaches the critical threshold and turns on the alarms in the emergency management organization, which is named as T_0.
- The period after the event reaches its critical threshold, which is named ***T+***.

Notice that ***T- and T+*** *are* periods of time before and after to the initial impact of the extreme event, and T_0 is a defined instant of time.

In agreement with an ICS, a scalable reaction of the emergency organization is expected depending on three factors: extreme event features, extension of the timeframe named ***T-,*** and location affected.

The initial state *State_Event* represents the ordinary condition in which the organization executes its tasks; the evolution of the event in *T-* is regulated for both differential equations sets and communities of states. The values of the adjacency matrix of the *digraph* show the ties among the nodes according to the established procedures in the ICS.

At the time T_0 (which is regulated by the set of differential equations of the SD model) a transition triggers an alarm to the whole *digraph*, a subset of it, or only to one node.

The community of states of transition enables the creation of transition branches for either sending the control to more than one state or for evaluating some clause before selecting the better suited state according to the clause. This characteristic presents enormous advantages for modeling the network centric scenario given that the community of states takes the role of a *high control* that regulates the behavior of the nodes, events, and interactions.

Therefore, branch dynamics destination states could be well suited to replicate how in real life an ICS performs its communications and tasks.

In Figure 40, we show a proposed model of *high control* which is a composite of concurrent and sequential states to control the local, state, and federal levels.

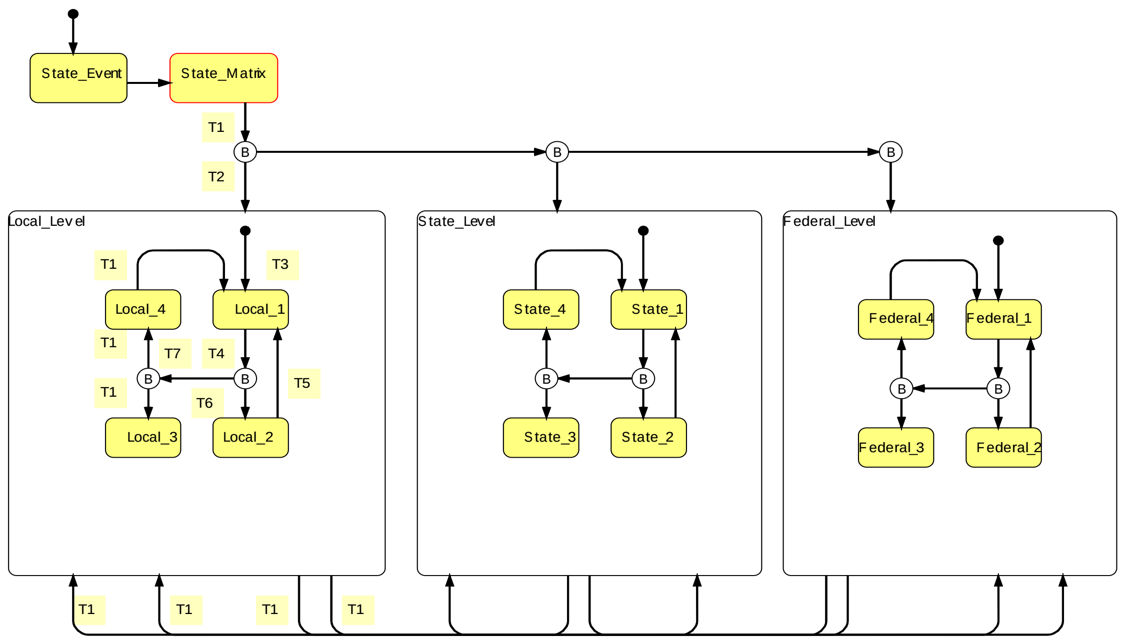


Figure 40: Organizational control based on state of transition

Using the UML definitions we suggest that the *community of states* emerges from the interactions of the global composite that resides in the main object and the composite states that reside in each object that represents a node of the emergency structure.

A modeler that uses the community of states as a mechanism of control has four tools for controlling the model:

- To define the sequence of states to control the possible extreme events.
- To modify the parameters of the objects in the model, for testing a selected measure of performance.

- To close and open connections according to historical cases, modifying in this way the adjacency matrix.
- To modify the discrete parameters in the nodes such as resources, time in queue, and utilization.

The algorithms that control the connections of the adjacency matrix should be the result of the analysis of historical cases in which the chain of command of the emergency management structure was interrupted either by the extreme event or its consequences. At this time, we make emphasis regarding the significance of this hybrid approach, since the mechanism of control based on *state transition* allows an evolution to the adjacency matrix, and as a result new interpretations based on social network analysis can be made for projecting the performance of the complete emergency structure.

This methodology does not present a fully developed internal behavior of the nodes, and it is limited on purpose to a simple approach based on discrete entities that arrive to the nodes, and then are processed and sent to others nodes according to the adjacency matrix.

The type of entity that arrives at a node *ni* is a function of the sender node *nj,* thus we could emulate the distribution probability that a real command and control system has performed in real situations.

Table 29 shows the attributes' data that a sender and a receptor could transfer between them in a standard formatted message of a real command and control system.

Table 29: Attributes of the data transferred between two nodes

Organization
Date and time
Sender identification
Receiver identification
Message type
Priority
Resources

Figure 41 portrays a layout of the internal nodes' behavior, and since we have defined six types of roles in the *digraph,* the behavior of each role in the emergency structure is modified according to different parameters applied to each object. Basically the interactions inputs (I) and outputs (O) are made in the dyad placed in the asymmetric adjacency matrix.

In accordance with the node's role and position in the organizational structure, it will require a certain number of pieces of data for processing and will produce one unit of information. We assume that the incoming data is combined with internal data produced by the node. Thus for each piece of data that is internally produced one piece of information is generated that is sent as output to the dyads in the adjacency matrix.

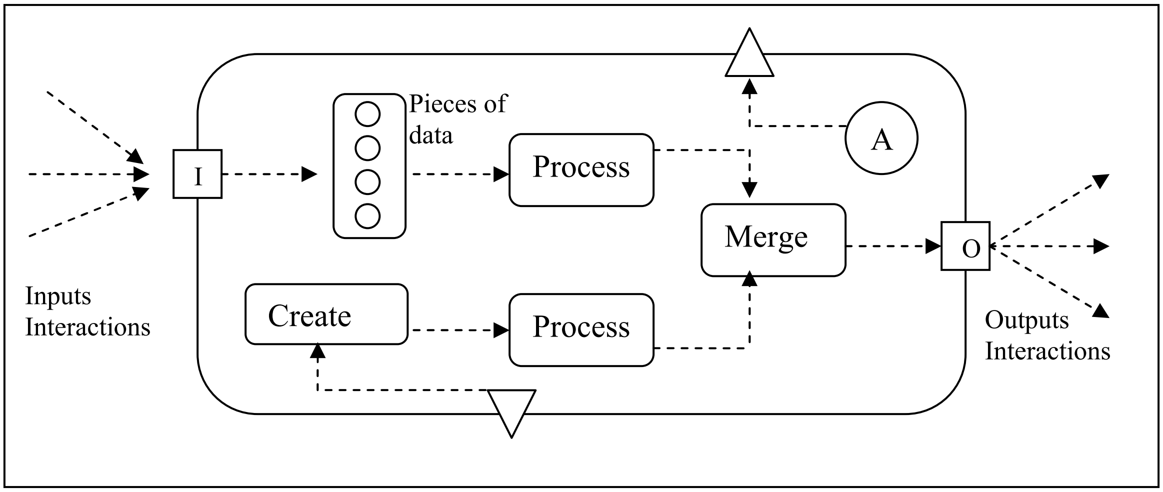


Figure 41: Internal node behavior (Implemented with Anylogic software)

The *Agent A* based on states of transitions accomplishes four tasks in the internal node behavior:

- Regulates the discrete behavior according to the type of event and parameter evolution of the external environment.
- Opens or closes the connections in the adjacency matrix, modifying the asymmetry in the *digraph.*
- Communicates to the external environment any continuous variables that might be required by another object.
- Communicates to the internal environment any continuous variables that might be required by the internal objects in the node. This task also might be accomplished by an interface variable which is shown as a triangle in Figure 29.

An example of the dynamic modification of parameters by means of Agent *A* or a continuous interface variable is shown in Figure 42. Given an exponential distribution of probability with parameter β_0 to an object source that generates internal entities in the node, either the *Agent A* or the continuous interface variable might change the parameter in time by a continuous set of parameters $\beta_1, \beta_2 \ldots \beta_n$ and thus reach a required behavior that evolves according to the surrounding environment.

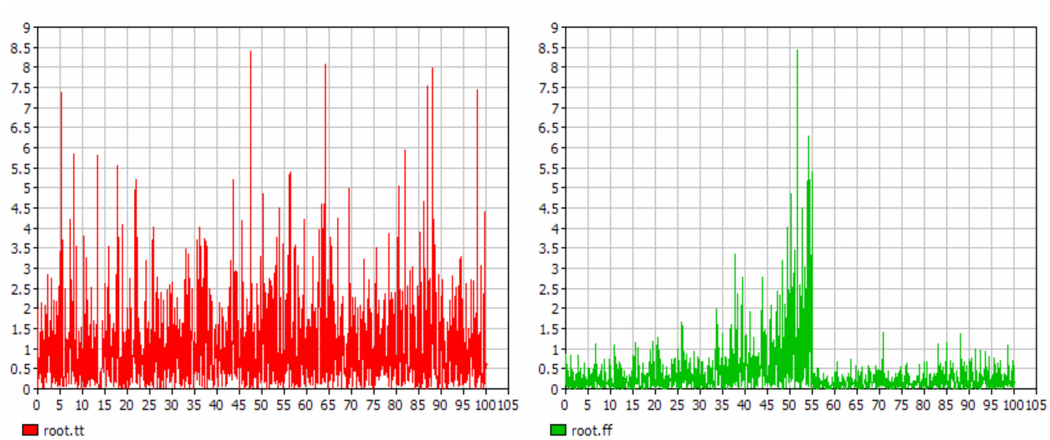


Figure 42: Evolution of the generation of entities according to dynamic parameters

An example of the cognitive domain was implemented based upon a SD model designed by Rudolph and Repenning (2002). Two variables of states combined with a set of in-flows, out-flows, and constants allow quantifying the positive and negative effects of stress in a node.

Basically, the model is composing of the following sequence:

- A variable of state provides quantification of the number of interruptions currently pending.
- The rate at which interruptions arrive is an exogenous variable.
- A rate confronts and resolves interruptions. Interruptions handled incorrectly stay in the stock of *interruptions pending*.
- The *desired resolution rate* represents the system's perception of how fast it needs to resolve interruptions. The *desired resolution rate* is equal to a first order exponential

smoothing of the indicated rate. The *smoothing* represents the delay in perceiving change in the number of *interruptions pending*.

- A rate shows how interruptions should be resolved in order to achieve the *desired resolution time.*
- *Stress* is equal to the ratio of the desired and normal resolution rates. The higher the *desired resolution* rate relative to how the system normally performs, the higher the *stress*.
- A variable captures the positive influence of *stress* on *productivity.* It is captured by an upward sloping table function that uses stress level as an input.
- A variable captures the negative impact of *stress:* As the system is overwhelmed, its ability to resolve interruptions decreases. It is captured by a downward sloping table function that uses *stress* level as an input.

In accordance to the performance of the model shown in Figure 43, the dynamics of the variables is different if it operates on the upward or downward sloping portion of the Yerkes-Dodson curve.

An agent built as a state of transition gathers the most significant variables from the mathematical structure of the model. Those variables are used for modifying the behavior of the node named *Hospital_1_A.*

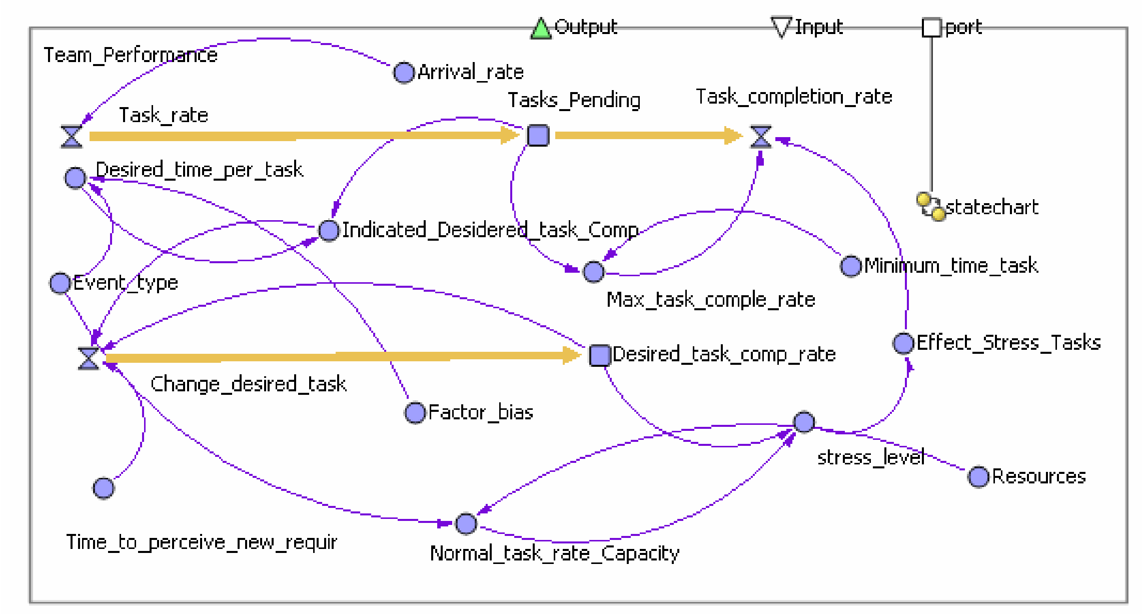


Figure 43: Example of a model for capturing the cognitive aspects of a node

<u>*The digraph* measures from a dynamic adjacency matrix</u>

In Chapter Five we defined three types of network properties; here we analyze the dyads and triad census, network properties, and one-mode metrics, and finally we will present some inferences regarding two-mode networks.

All the analysis was made over the hypothetical *digraph* which was built based on an ICS.

Sub-set measures: Dyad and Triad

The *dyads* were obtained from the *digraph* and compared with the expected values of a random digraph that contain the same number of nodes and connections. The number of Monte Carlo simulations was 10,000. The results are shown in Table 30.

Table 30: Observed and expected values in the digraph

Dyad Type	Observed	Expected(Mean)
Mutual	55	35.803
Asymmetric	67	86.197
Null	544	544

From Table 30 we can conclude 55 relationships have reciprocity in the procedures for transferring information. On the other hand 67 flows are sent to others nodes and the node sender should not wait for feedback from the node receptor; essentially there connections are asymmetric. Finally, 544 dyads do not present any connection.

Wassermann et al. (1994), among others, suggested that a dyadic analysis seeks to answer several questions about mutual, asymmetric, and null relationships:

- How might we compare the fraction of mutual dyads either with a theoretical prediction or a similar organizational digraph?
- Are mutual dyads statistically more prevalent than other kinds of dyads in the ICS?
- Are the dyadic relationships more mutual and less asymmetrical than other comparable organizations?

We apply Markov chain Monte Carlo (MCMC) method test to generate random matrices with a set of given parameters. Thus, testing of a hypothesis is possible to perform between the observed and expected values. The number of simulation adjacency matrices used for the expected values were 10,000 matrices.

We showed that the total number of *triads* in a *digraph* is given by $\binom{n}{3}$.

We will examine the *triad census* according to the *Balance-Theoretic Models*; the characteristics of six models will be contracted with the results of the column *Observed* in Table 31. Each model is gradually less restrictive that the previous ones.

Our goal is to find statistical patterns that can be evaluated to gain knowledge regarding the structure of an incident command system, and as a consequence, to forecast its performance. Nooy et al state that unfortunately, the social network systems barely ever conform perfectly to a balance-theoretic model, and most of the time a type of *triad* occurs at least once. Nevertheless we must compare the *triad census* with the distribution expected by chance of a digraph, since if a certain type of *triad* occurs more often, we may assert that a determined model guides the behavior of the complete digraph. (Nooy et. al. 2005).

Balance model: It represents the symmetric connections between the nodes and has up to two clusters in the configuration. Our emergency structure presents 30 *Triad 300* and 1,266 *Triad 102* whose observed frequencies are statistically different from the expected triads obtained from a random digraph (Table 31), this relative difference shows a tendency toward a balance model. The chi-square statistic is highly significant which helps us to confirm the tendency.

Clusterability model: This model is less restrictive and permits more than two clusters in the digraph. This configuration includes the *Triad 300*, *102* and *Triad 003*.

In Table 31 we observe 4,363 *Triad 003* and 3,268 expected *Triad 003*.

Since we are studying a network centric environment, this model must be prohibited in the emergency organizations because it represents the presence of clusters (components in graph terminology) that do not permit a distributed decision making.

Ranked clusters model: This model permits asymmetric connections from each node to all nodes on higher ranks. Notice in Table 31 the statistical difference between the observed and expected values of the *Triads 021D, 021U* and *030T*-all of them can exist in this model. There are two more *triads* permitted in this model, *Triads 120D and 120U;* whose observed and expected values also are statistically different.

The presence of a statistic difference in the *triads* with symmetric connections implies that the relationships between the nodes are not hierarchical and have high feedbacks, which could be critical when they are required to transmit information quickly and the decisions must be immediate.

Transitivity model: In the analysis of the emergency configuration, this model introduces the concept of *transitivity*, where all the *triads* with a path of length two are closed from the initial node (n_1 connects to n_2, n_2 connects to n_3 then n_1 connects to n_3). The *digraph* presents 1,428 *Triad 012* and the expected value is 3,044 in the model, which implies that the *digraph* is not transitive.

Hierarchical clusters model: In addition to the previous *triads*, this model permits the *Triads 120C* and *210*. Since asymmetric *dyads* exist, they are interpreted as a form of ranking in the organizational structure, therefore the asymmetric connections should not permit any cycles. According to Table 31 we compared 22 *Triad 120C* and 42 *Triad 210* against an expected value of 11 and 1.7 respectively, which means that the configuration has a tendency toward the hierarchy.

Table 31: Observed and expected triad values (Report from Pajek software)

Type	Number of triads (ni)	Expected (ei)	(ni-ei)/ei	Model
3 – 102	1266	236.34	4.36	Balance
16 – 300	30	0.05	654.55	Balance
1 – 003	4363	3268.67	0.33	Clusterability
4 - 021D	37	236.34	-0.84	Ranked Clusters
5 - 021U	46	236.34	-0.81	Ranked Clusters
9 - 030T	15	73.38	-0.80	Ranked Clusters
12 - 120D	18	5.70	2.16	Ranked Clusters
13 - 120U	17	5.70	1.98	Ranked Clusters
2 – 012	1428	3044.71	-0.53	Transitivity
14 - 120C	22	11.39	0.93	Hierarchical Clusters
15 – 210	42	1.77	22.75	Hierarchical Clusters
6 - 021C	89	472.68	-0.81	Forbidden
7 - 111D	142	73.38	0.94	Forbidden
8 - 111U	142	73.38	0.94	Forbidden
10 - 030C	6	24.46	-0.75	Forbidden
11 – 201	107	5.70	17.78	Forbidden

Chi-Square: 28914.5328***
2 cells (12.50%) have expected frequencies less than 5.
The minimum expected cell frequency is 0.05.

Network measures

In recent years, researchers have found similar patterns in the configurations of dense networks, such as chemical interactions, the Internet, citations in books, the World Wide Web, etc., and they have generated a set of rules of thumb for enhancing the desired characteristics of robustness, tolerance to failure, adaptability, flexibility, etc. We argue that current systems based on command and control provide enough data for determining the desired properties of a standardized ICS.

In Table 32 we showed the main properties obtained from the digraph as a whole.

We will discuss some of these measures and will make inferences about desired properties in a digraph which represents an ICS.

According to our experiments, the number of nodes in the digraph is 37, but most of the time an ICS in the federal, state and local levels will have more than 100 nodes, especially if we include private and non governmental organizations in the process of making decisions.

The number of connections in the adjacency matrix is 179. Care (2005) provides rules of thumb for military networks according to the number of nodes. He suggests: connections<<2N (too brittle), connections=~2N (desired value) and connections >>2N (possible overhead).

We recommended that the number of connections will emerge as a realistic parameter when data coming from the database of the command and control systems can be analyzed. Meanwhile we should test the hypothesis of a range between 2N <connections<4N. Our suggestion is based on the previous analysis of the ICS and the five case studies.

In the digraph the density is 0.13; it shows the proportion of the number of connections present to the maximum possible. This measure should be studied in parallel to the number of nodes and the ego-digraphs produced in the organizational structure, because some clusters might concentrate most of the connections. Nevertheless we suggest values over 0.30 might demonstrate a lack of hierarchy and overflow in processing data and resources.

The average degree of the digraph is 4.78. This index should be compared with the degree distribution shown in Table 34, since the number of isolated and pendant nodes could affect the performance of the organization, especially if one of them plays a critical role in the whole structure.

The inclusiveness index for both in-degree and out-degree helps us to distinguish weak connections. The first one has a value of 95% and the second one 100%.

The reciprocity index is 0.62. This is linked to the *dyads census* and provides an overall view of the feedbacks produced in the digraph.

The transitivity index is 0.38. This enables us to characterize the whole digraph with tendency toward the transitivity.

The diameter index is 6. This value is the largest geodesic distance between any pair of nodes in the digraph, which means that there exists at least one node that must send its data or resources through five nodes before arriving at the receptor node. We suggest that an ICS should not have path larger than 4.

Finally the index hierarchy is equal to 0.2 and provides a strong overall measure for inferring the proportion of the number of nodes with asymmetric connections to all nodes.

Table 32: Digraph measures of the emergency organization

Property	Value
Nodes	37
Connections	177
Density	0.13
Average Degree	4.78
Inclusiveness	1
Reciprocity	0.62
Transitivity	0.38
Clustering Coef.	0.64
Mean Distance	2.48
Diameter	6
Connectedness	0.79
Efficiency	0.89
Hierarchy	0.2
LUB	0.99

Table 33: Distribution of degree

Measures	In-degree	Out-degree
Sum	179	179
Mean	4.83	4.83
Std.Dev	3.41	3.33
Min	0	1
Max	14	14
Number of isolated	2	0
Number of pendant	5	4
Inclusiveness (%)	94.59	100

Table 34: Node Type in the *digraph*

Isolate	Transmitter	Receiver	Carrier	Ordinary
0	2	0	1	34

There are no nodes with degree equal to zero, and four nodes only transmit data and do not receive information from others nodes. One *node* shows in-degree and out-degree equal to one and it is classified as a *carrier node.* The others thirty-two *nodes* are classified as *ordinary nodes* since they have both in-degree and out-degree greater than 1.

The *digraph* does not have a *bridge connection* that implies vulnerability because removing it might disconnect the *digraph.*

One mode measures

In Chapter Four we defined three sets of measures to examine the individual properties of the nodes: *centrality; neighbor; and connection* measures. In Table 35 we show twelve measures, which are representatives of the three sets and we describe possible influences of the values in the performance of the whole structure of the organization.

By each node, the first two columns depict the in-degree and out-degree connections in the ICS. Maximal values such as *Mayor* and *Incident Commander* provide an initial indicator of the position and role of these nodes in the digraph. Minimum values such as *Sensor* and *Red Cross* also require attention regarding their role in the structure. The 3rd and 4th columns called *degree centrality* standardize the degree measures for comparing those with others ICS digraphs. Notice that the *centrality* index plays a fundamental role for knowing the hubs in a dense ICS, but it does not necessarily mean that nodes with a high centrality degree are most significant in the digraph. For instance, the node *Sensor* has a centrality in-degree equal to 0.0 and an out-degree equal to 0.028 and in accordance to our model most of the time this node triggers the alarm warning that activates the complete emergency system.

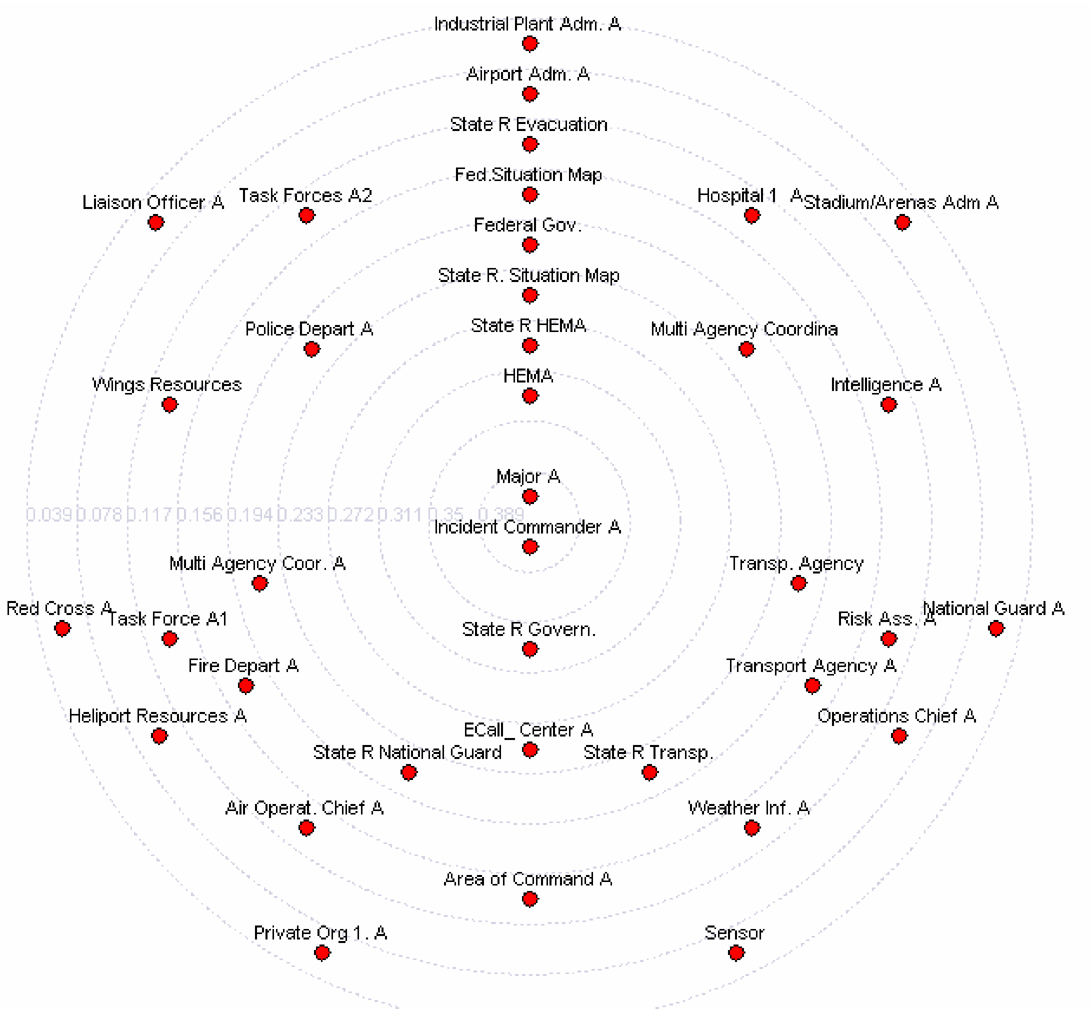


Figure 44: Centrality measures of the digraph

Figure 44 shows a concentric analysis of the in-degree centrality of the digraph. The nodes with highest values are in the center of the figure and the lowest values are in the periphery. Notice the position of the nodes that belong to the federal and state levels (blue and green nodes), they are located in the intermediate area of the figure. On the other hand, the local nodes (red color) are still in the periphery of the figure with values close to zero, except the nodes *Incident Commander* and *Mayor A*, which are the most central with a value of 0.389.

Table 35: Selected measures of each node in the digraph

Node	In Deg.	Out Deg.	Centrality In	Centrality Out	Ego Size	Ego Density	Eigen Vector	Closeness In	Closeness Out	Min Cutset	Betwee-ness	Flow Btwn
Air Operat. Chief A	4	1	0.11	0.03	5.00	0.60	0.03	0.41	0.19	0	0.05	462
Airport Adm. A	2	2	0.06	0.06	3.00	1.00	0.07	0.35	0.22	0	0.00	224
Area of Command A	4	5	0.11	0.14	6.00	0.47	0.06	0.39	0.23	0	0.04	624
ECall_ Center A	8	4	0.22	0.11	10.00	0.44	0.16	0.44	0.26	0	0.06	834
Fed.Situation Map	5	5	0.14	0.14	6.00	0.67	0.19	0.36	0.23	0	0.00	831
Federal Gov.	6	7	0.17	0.19	7.00	0.71	0.24	0.42	0.25	0	0.02	968
Fire Depart A	5	5	0.14	0.14	8.00	0.50	0.10	0.43	0.25	0	0.03	613
Heliport Resources A	2	2	0.06	0.06	3.00	1.00	0.02	0.40	0.16	0	0.00	221
HEMA	10	9	0.28	0.25	11.00	0.60	0.34	0.50	0.25	0	0.08	1341
Hospital 1 A	3	3	0.08	0.08	5.00	0.10	0.07	0.35	0.24	1	0.06	284
Incident Comm. A	14	13	0.39	0.36	19.00	0.22	0.22	0.57	0.27	0	0.42	1914
Industrial Plant A	1	4	0.03	0.11	5.00	0.50	0.06	0.31	0.22	0	0.00	186
Intelligence A	4	3	0.11	0.08	4.00	1.00	0.05	0.39	0.22	0	0.00	513
Liaison Officer A	0	2	0.00	0.06	2.00	1.00	0.05	0.37	0.23	0	0.00	237
Mayor A	14	14	0.39	0.39	19.00	0.26	0.33	0.49	0.28	0	0.27	1743
Multi Agency A	6	3	0.17	0.08	6.00	0.60	0.16	0.42	0.24	0	0.01	473
Multi Agency Coor.	7	4	0.19	0.11	7.00	0.67	0.20	0.42	0.21	0	0.01	825
National Guard A	0	3	0.00	0.08	3.00	0.67	0.07	0.29	0.24	0	0.00	287
Operations Chief A	2	5	0.06	0.14	6.00	0.60	0.05	0.39	0.22	0	0.08	593
Police Depart A	6	4	0.17	0.11	7.00	0.62	0.11	0.44	0.25	0	0.02	749
Private Org 1. A	1	1	0.03	0.03	2.00	1.00	0.03	0.34	0.21	0	0.00	90
Red Cross A	0	1	0.00	0.03	1.00	0.00	0.01	0.00	0.24	0	0.00	0
Risk Ass. A	4	3	0.11	0.08	4.00	1.00	0.05	0.39	0.22	0	0.00	485
Sensor	0	1	0.00	0.03	1.00	0.00	0.01	0.00	0.24	0	0.00	0
Stadium/Arenas A	1	3	0.03	0.08	4.00	1.00	0.05	0.34	0.21	0	0.00	350
State Evacuation	4	9	0.11	0.25	9.00	0.56	0.24	0.39	0.25	0	0.01	876
State Govern.	10	7	0.28	0.19	12.00	0.42	0.28	0.51	0.24	0	0.08	1406
State HEMA	9	10	0.25	0.28	14.00	0.46	0.31	0.44	0.27	0	0.10	1520
State Situation Map	8	10	0.22	0.28	10.00	0.58	0.32	0.48	0.27	0	0.10	1219
State Transp.	6	7	0.17	0.19	9.00	0.47	0.20	0.41	0.25	0	0.03	1079
State National Guard	6	5	0.17	0.14	6.00	0.67	0.20	0.40	0.24	0	0.03	813
Task Force A1	3	3	0.08	0.08	3.00	1.00	0.05	0.38	0.22	0	0.00	338
Task Forces A2	3	3	0.08	0.08	3.00	1.00	0.24	0.38	0.22	0	0.00	338
Transp. Agency	6	8	0.17	0.22	9.00	0.47	0.22	0.37	0.24	0	0.01	1102
Transport Agency A	5	2	0.14	0.06	5.00	0.60	0.11	0.37	0.23	0	0.00	346
Weather Inf. A	4	4	0.11	0.11	5.00	0.80	0.05	0.39	0.22	0	0.00	532
Wings Resources	4	2	0.11	0.06	5.00	0.40	0.03	0.43	0.16	0	0.01	333

The local connection structure of each node in the digraph is represented by the values of ego-size and density. Because density is inversely proportional to the ego-digraph size, (the number of possible connections increases rapidly with the number of nodes, whereas the number of connection usually is limited), Nooy et al. (2005) suggest considering alternative measures, nevertheless in the context of an ICS, the density measures provide an intuitive glance of the cohesion of the local structure of a node and its dyads connection. For instance the nodes; *Task Force A1* and *Task Force A2* present a density of 1, which demonstrates a high cohesion with the three nodes that each one has with its dyads.

Eigenvector centrality of a node is recursively proportional to the sum of eigenvector centralities of the nodes connected in the digraph. The *High Emergency Management Agency* and the *Mayor A* present the highest value in the eigenvector centrality of the ICS because they are connected to many nodes which also are well-connected.

Closeness measure changes the concept of centrality by the geodesic distance of the nodes, an issue that in an extreme event could be more significant than a traditional degree centrality measure. The reason is simple: a network centric environment such an *Incident Command System* requires reaching the whole emergency structure in the least amount of time possible. From Table 35 two nodes help us to understand this measure; the node sensor presents a closeness centrality in-degree of 0 because it does not interact with any other node. On the other hand the node *State_R_Governor* whos*e* closeness in-degree value is 0.51 shows that this node is the best situated for quickly reaching any other nodes in the emergency organization. The minimal node cutset is the node *Hospital 1 A*. If it is removed the digraph will be separated in three components. This measure enables us to identify the vulnerability of the transference of flows in the ICS and to find out where the ICS could be disconnected with severe consequences for the whole system.

The column betweenness centrality shows that the *Incident Commander* node has the highest proportion value (0.42) of all geodesic connections between pairs of other nodes. Notice the large difference with the second position obtained by the *Mayor A* node (0.27). This index is critical if we assume that the flows and resources go by the geodesic path in an ICS.

The *dependency matrix* shows the dependency that the 37 nodes have among them when a node source sends flows to other nodes. The highest values are the connections between the *Sensor* and *Hospital 1* and the *Red Cross* and *Hospital 1*, both with a value of 34.

In order to find out the underlying data structure of the *one mode* measures and to reduce the amount of correlated indexes we applied principal component analysis to the twelve digraph measures. We used correlation matrix to standardize the measurements because they do not have the same scale.

Eigenanalysis of the Correlation Matrix

Eigenvalue	7.9607	1.5701	0.9298	0.6433	0.3783	0.2669	0.1289	0.0670
Proportion	0.663	0.131	0.077	0.054	0.032	0.022	0.011	0.006
Cumulative	0.663	0.794	0.872	0.925	0.957	0.979	0.990	0.995

Eigenvalue	0.0321	0.0222	0.0004	0.0003
Proportion	0.003	0.002	0.000	0.000
Cumulative	0.998	1.000	1.000	1.000

Variable	PC1	PC2	PC3	PC4
In_d	0.337	-0.070	0.103	-0.129
Out_d	0.337	0.013	-0.102	0.102
Cen_In	0.337	-0.073	0.098	-0.132
Cen_Out	0.337	0.013	-0.107	0.089
Ego-size	0.347	0.019	0.040	-0.147
Ego-de	-0.125	-0.669	0.116	0.324
Eigenv	0.302	-0.082	-0.132	0.472
Clos_In	0.236	-0.436	0.470	0.029
Clos_Out	0.245	0.303	-0.325	0.463
Cutset	-0.025	0.480	0.761	0.371
Between	0.286	0.136	0.140	-0.495
Flow_Bet	0.347	-0.071	-0.026	0.010

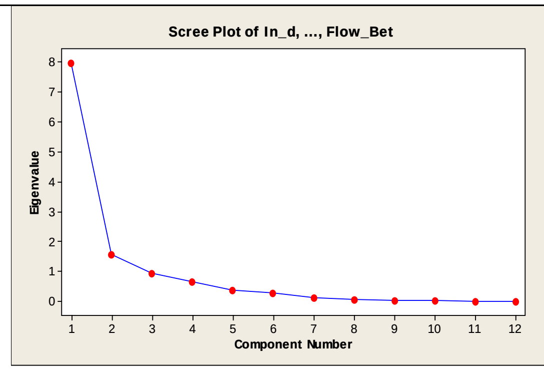


Figure 45: Principal component analysis of Table 35

The first principal component has variance 7.96 and accounts for 66% of the total variance. This is representative of ten measures from Table 35, except the ego-density and cutset indexes. The component depicts a contrast between two groups of variables, the first is formed by the ego-density and cutset indexes and the second group formed by the other ten measures. This issue is confirmed if we calculate the Pearson correlation between each pair of variables. According to the test of correlation:

$$H_0: \rho = 0 \text{ versus } H_1: \rho \neq 0 \quad \text{where } \rho \text{ is the correlation between a pair of indexes}$$

The p-values of the indexes ego-density and cutset showed values greater than 0.05 which demonstrate that there is no evidence of a linear relationship between the two measures and the other ten indexes. The second principal component has variance of 1.57 and accounts for 13% of the data variability. The third principal component has a variance of 0.92 and account for 7.7 % of the data variability. In Figure 45 a plot of the eigenvalues associated with their component show the magnitude of the three selected components.

Because of the lower value of the variance in the fourth component, we suggest that the data structure in Table 35 can be captured with the first three components, which represent the 66 %, 79 % and 87% of the total variability.

Experimental analysis

Experiment 1: System dynamics – Discrete event simulation

Description

We tested the combined behavior of the object *electric_power_system* and the discrete behavior of the nodes that form the organizational digraph. The goal was to identify the most comprehensive mechanism for modeling the influence of continuous events over the discrete behavior of the nodes, particularly the parameters of the objects that generate new entities.

Conditions

According to our findings, we suggested two types of hybrid implementations between a SD and a DES model. The first was built by means of an *interaction of variables*, using the concept of *dynamic simulation.* The second one was built by means of an *interaction of models*, using an external control that modifies at run time the internal parameters of the nodes.

The model with 37 nodes was set up to run during 30 time units.

Conclusion

The *interaction of variables* required an external interface for sending the level of electricity *s* which is produced in City 1. The dynamic parameter was passed to the inter-arrival exponential time of the object creation, such as *exponential(s/20)*.

Figure 45 shows the throughput (red curve) of the node *Sensor* which sends new signals to the rest of the emergency system according to how the level of electricity in City 1 decreases (green curve).

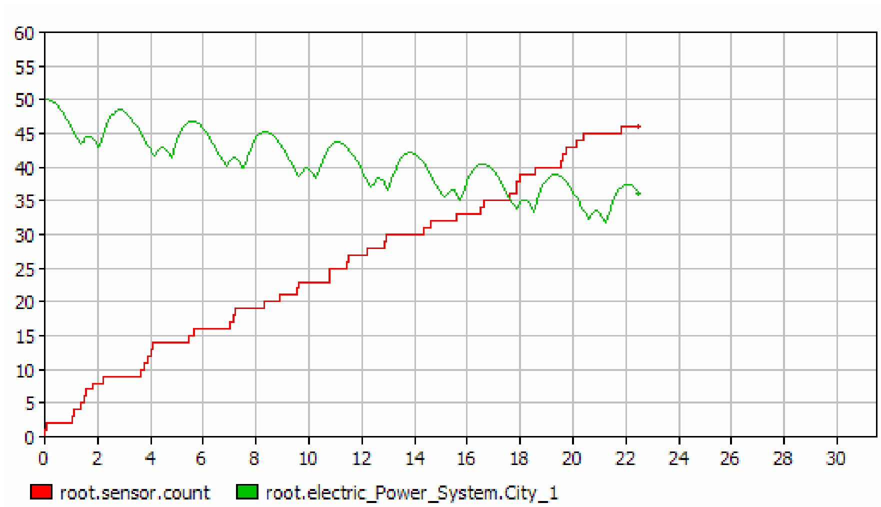


Figure 46: Dynamic simulation by mean of *interaction of variables*

The second implementation tested was *interaction of models*. This tool requires an interface between the SD and DES models.

When the electrical power either fails or reaches a critical level, a set of *state- transitions* sends a signal to another *set of state transitions* in which reside in the node *Sensor*. Both *state-transitions* are shown in Figure 46. Notice the strong difference comparing with the *interaction* *of variables,* because by using *state-transitions* as an interface, the modeler must define critical thresholds that modify the generation of entities in the internal behavior of the node *Sensor.* The generation of entities in the time is shown in Figure 47.

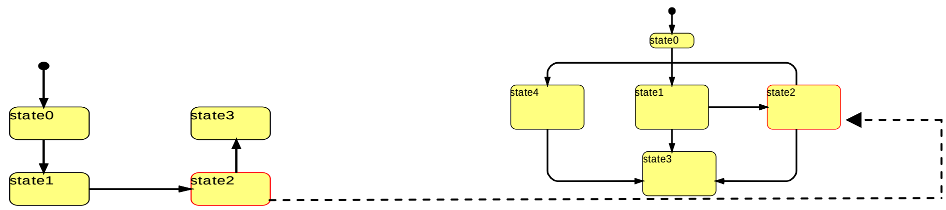


Figure 47: Set of state-transitions between a SD and a DES model

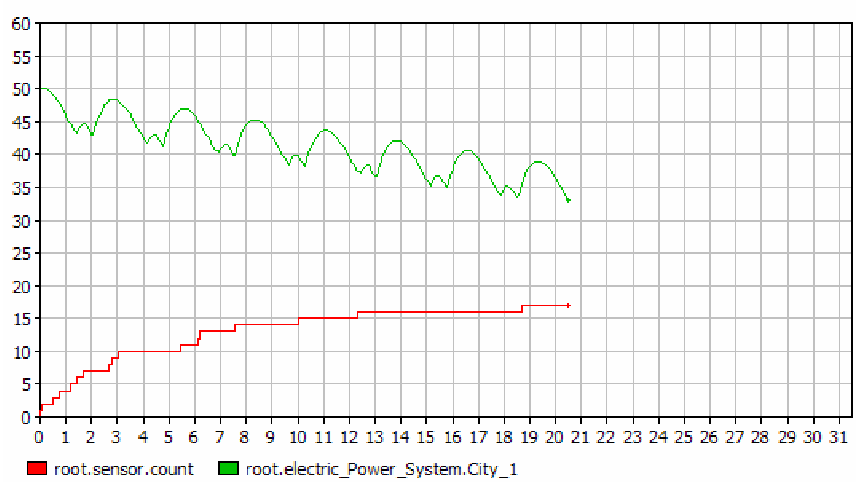


Figure 48: Behavior of the SD and DES simulations governs by a set of state-transitions

Nevertheless both techniques provide additional tools to the modeler and permit an implementation of a more complete simulation than either an isolated SD or DES model. The *interaction of variables* is better situated when there exists a validation of the influence of the continuous variables over the discrete and vice versa.

On the other hand, *interaction of models* is well situated when the modeler does not know exactly how the model will evolve and requires controlling it by means of *state transitions*.

Experiment 2: System dynamics—Community of states—Discrete event simulation and digraph analysis

Description

We tested a SD model embedded into the hybrid model. Since the whole model presents many parameters and variables, which most of the time are difficult to control, we designed a high control based on the defined concept of *community of states*. The high control categorizes the data coming from different simulation techniques, and sends it to a selected composite of states to process and finally to generate new data which will be sent to the digraph. We will summarize how a social network analysis enhances the study of the performance of the whole model.

Conditions

The node tested, *State_Map* was defined as a instance of the class *Situation_Awareness.* The parameters were incorporated to the object *State_Map* according to the rules that govern the position of the node in the digraph. Figure 48 shows the high control formed by three composite states: federal, state and local. In accordance to the data received from external models, the high control sends the signal to a selected composite state. Notice that the interactions of the dyads can be governed from the high control (named as *community of states*).

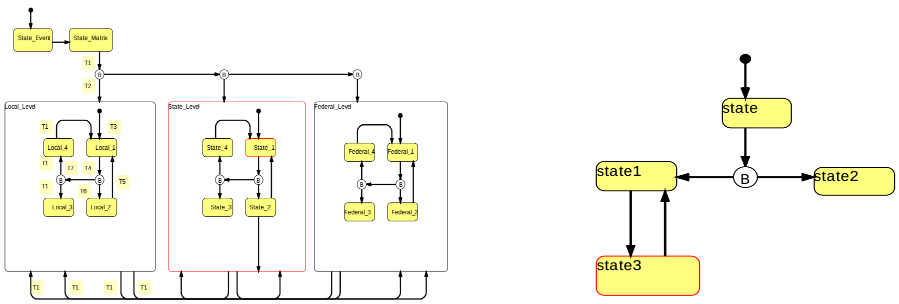


Figure 49: *Community of states* formed between the high control and the *state transition* of the node *State_Map*

<u>Conclusions</u>

The mechanism implemented regulates the sequence of three types of simulation paradigms: SD- *states transitions*- DES.

We concluded that the implementation of a high control is a unique form to manage the sequences, parallelism of actions, activation of alarms and hierarchies in a hybrid model that emulate an ICS.

The high control enables a test of the diffusion of data through the complete digraph. Nevertheless, the complexity of the model requires a topological analysis based on the social network techniques previously developed.

In order to enhance our conclusions, we summarized an analysis of the *ego- digraph* of the node *State Map* (Figure 49) which fired the initial alarm in the organization.

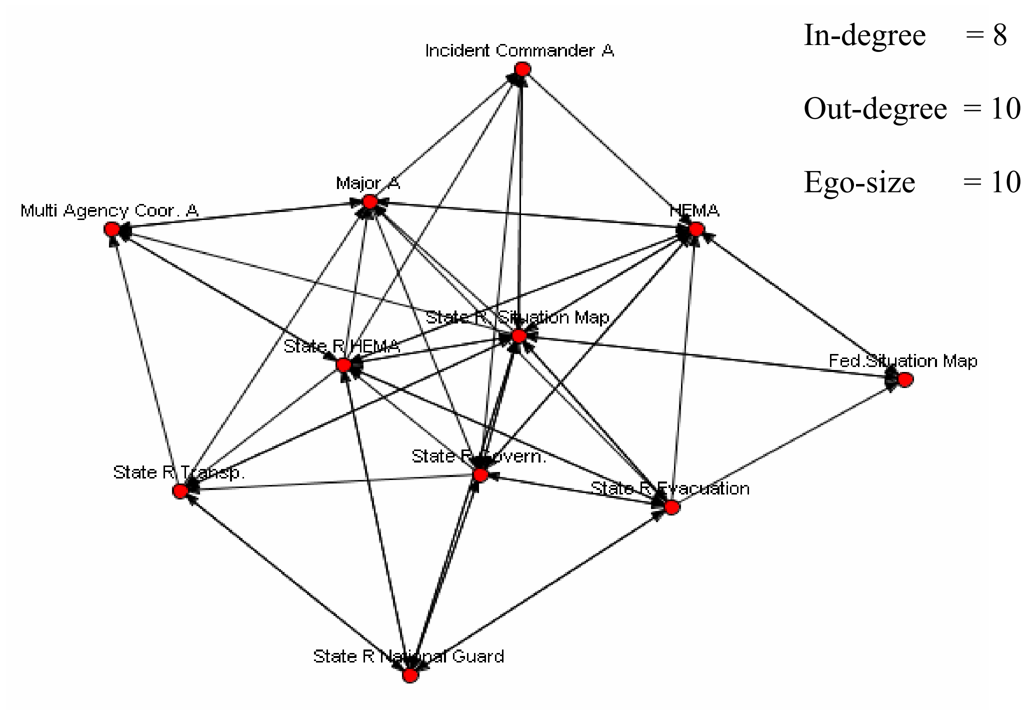


Figure 50: Ego-digraph formed around the tested *State_Map* node

The focus node has a 10 out-degree and an 8 in-degree, thus we can infer that there are two nodes that require to use others nodes for sending data to the *State_Map.* Nevertheless, in accordance to the concept of density, the focus node presents a high centralization (density=0.57), which makes sense since its role is sharing data and keeping the *situation aware* of its level.

Table 36 depicts the geodesic paths in the *ego-digraph*. A preliminary analysis of the matrix points out the critical position of the node *Multi_Agency_A* due to its extended average geodesic paths. For instance, it requires three steps to reach the *Federal_Map* node, and two steps to send feedback to the *State_Map* node.

Table 36: Geodesic path in the ego-digraph of the node *State_Map*

	F.M	HEMA	S.G	S.M	S.E	S.H	S.T	S.N	M.A	M.A	I.C
Fed. Map	0	1	2	1	2	2	2	2	2	2	2
HEMA	1	0	1	1	2	1	2	2	1	2	2
State Gov.	2	1	0	1	1	1	1	1	2	2	2
State Map	1	1	1	0	1	1	1	1	1	1	1
State Evac	1	1	1	1	0	1	2	1	1	2	2
State HEM	2	1	2	1	1	0	1	1	1	1	1
State Tran	2	2	2	1	2	2	0	1	1	1	2
State Nati	2	2	1	1	1	1	1	0	2	2	2
Mayor A	2	1	1	2	2	2	2	2	0	1	1
Multi Age A	3	2	2	2	2	1	2	2	1	0	2
Incid.Comm	2	1	1	1	2	2	2	2	2	2	0

Table 37 shows the *dyads census* performed over the *ego-digraph*; this analysis enables us to conjecture regarding the direct feedbacks that the eleven nodes will have in the elapsed time for the duration an extreme event.

Initially, researchers in network centric environments forecasted that a maximal network was the best solution for sharing data and resources (mainly influenced by the computer networks). Our model showed that those configurations delay the flows and most of the time are unnecessary. For instance, the *ego-digraph* presents 20 mutual dyads, which proves that the nodes will have an immediate feedback to the data transferred. In Table 37 we infer that 16 connections do not receive direct feedback and the data will be transferred through the others nodes. A statistic analysis regarding the patterns of the observed and the expected dyads could be made based on the data obtained from the organizational structure of an ICS.

Table 37: Dyads census in the ego-digraph of the node *State_Map*

Number of.	Observed	Expected (Mean)
Mutual Dyads	20	18.43
Asymmetric Dyads	16	17.56
Nulls Dyads	19	19

Another significant conclusion that arises from the *ego analysis* is that the level for managing the extreme event does not fit necessarily with the relationships produced in an ICS. For instance, in the ego-digraph the *Federal_Map* is a bridge between the state and federal level. The same case occurs with the *Incident_Command* which belongs to the same *ego-digraph* but corresponds to the structure of the local levels.

Additionally, Table 37 confirms that the node *State_Map* is the ego of the digraph since all its geodesic paths in the matrix have a value of 1.

The timing analysis and synchronization of the data is another advantage that produces a hybrid simulation merged with a digraph analysis (adjacency matrix). In Figure 50, we show that when the extreme event reaches an unsafe level, the composite state transfers a signal to the node *State_Map,* which is in charge of keeping the *situation aware* of its organizational level. At time 1, the node generates a piece of data that is transferred to its dyads. The amount of time that the node *State_Map* will take for distributing the data in the three levels of the emergency organization will depend on two features: the number of paths toward the nodes receptors, and the internal configuration of each node for processing the incoming data.

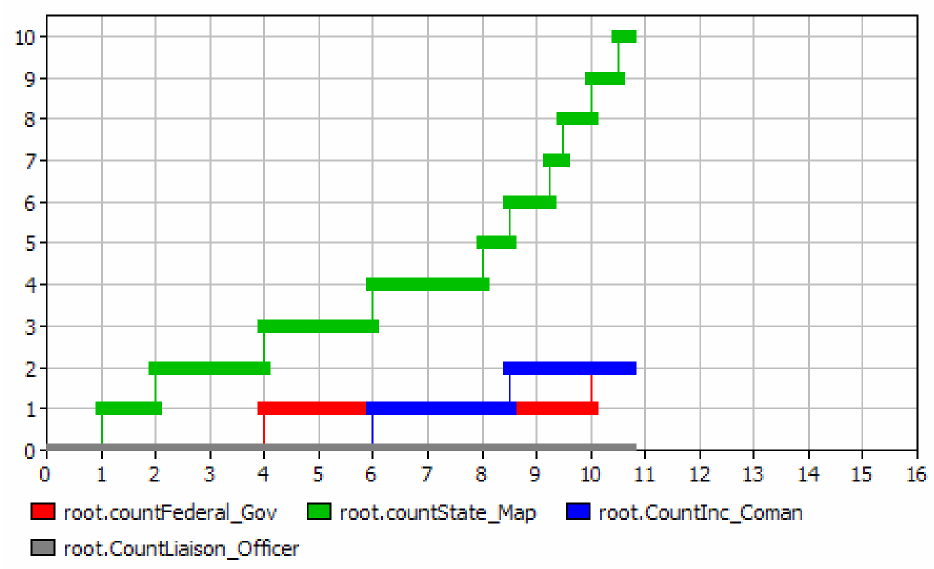


Figure 51: Number of entities generated in three different nodes.

We can distinguish that the *Federal_Gov* has a geodesic path of 2 with the *State_Map* and generated the first piece of data at time 4, which coming from its dyad *Federal_Situation_Map.* On the other hand, the *Incident_Command* node belongs to the *ego-digraph* but yields the first piece of data only at time 6 (2 time units after the *Federal_Gov*).

Finally, at time 11, the node named *Liaison_Officer* did not yield any piece of data. According to our methodology we infer two possible reasons: the first is the *geodesic path* of two steps that exist between the node *State_Map* and the node *Liaison_Officer;* the second is the high-degree centralization that presents the node *Incident_Command* which is a bridge for arriving to the node Liaison_Officer.

Experiment 3: Influence of cognitive modes (Yerkes-Dodson curve) into the internal discrete behavior of the nodes

Description

By using the hybrid model, a node incorporated a subclass which represents a mathematical model to understand the role of interruptions and stress in organizational collapse. The Yerkes-Dodson curve enabled us to demonstrate the relationship between the stress and the performance of the nodes. Initially the increasing stress enhances the performance of the node (short delay in the processes time), but after a period the performance decreases (extended delay in process time). The complete model was previously explained in Figure 43 (Rudolph and Repenning, 2002). We attempted to demonstrate that cognitive models are well situated in our methodology, and under an object oriented design they can enhance the validation of the internal behavior of the different nodes that compose an emergency management organization.

Conditions

To evaluate the influence of the SD model "role of interruptions and stress in organizational collapse" we built a class named *Team Performance* which was incorporated into the internal behavior of the node *Hospital_1_A*.

According to our theoretical description of the interrelationships between a SD and a DES model, we tested the influence of the continuous and discrete parameters in the final behavior of the node. (Notice that behavior means pieces of entities processed in the nodes.)

In execution time, the SD model took two dynamic parameters from the discrete model: number of resources and task arrival rate. On the other hand, at run time, the DES model took the variable *Effect_Stress_Tasks* to modify the *delay time* in the servers that process the data in the node *Hospital_1_A*.

Conclusions

The class *Team_performance* was incorporated as a subclass of the node *Hospital_1_A*.

The interaction of the two types of simulations was implemented by using an interface based on states of transitions. We found that the feedback loops of the SD model highly influence the stability of the continuous variable *Effect_Stress_Tasks* (see Figure 43).

In the same way, the parameters sent for the DES model produce a high instability in the SD model. In order to deal with this problem, we used two sets of states of transitions for putting boundaries on the thresholds that the model can reach.

The internal structure of the node *Hospital_1_A* is shown in Figure 51. It is an instance of the class *Support* which was defined in Chapter Four, Table 16.

The structure of the model allowed that the node parameters were fixed according to the position and role of the node in the digraph. Thus the methodology is open to incorporate many other nodes with an equivalent internal structure but that depict different either discrete or continuous behaviors.

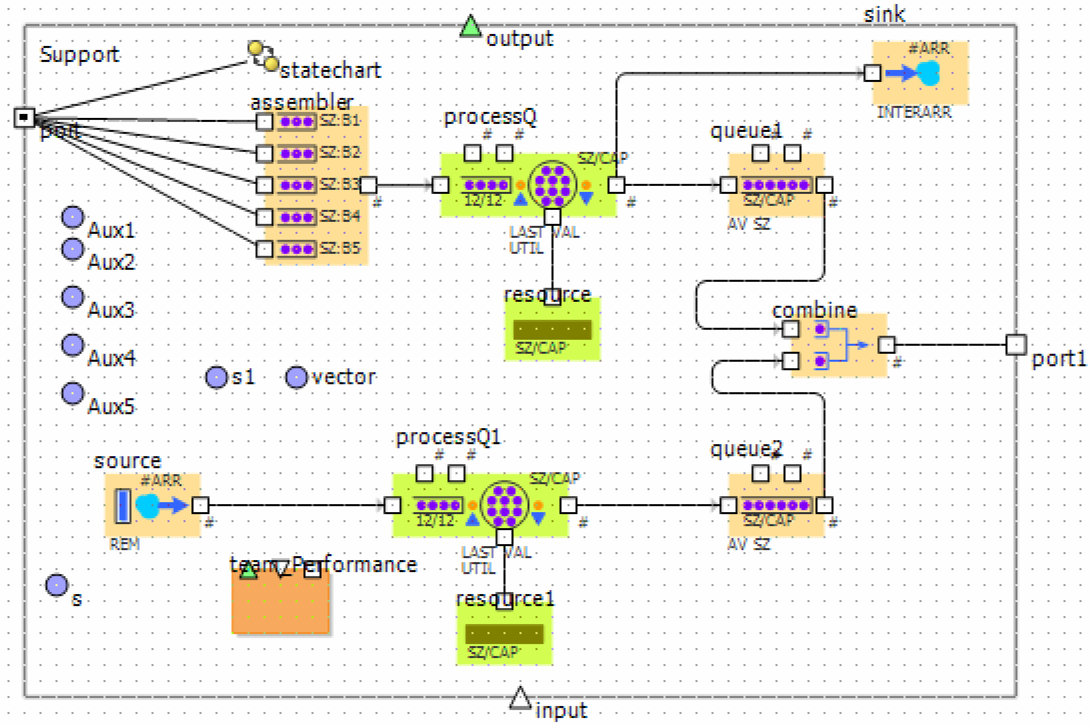


Figure 52: Internal structure of the node *Hospital_1_A*

Experiment 4: Community of states – Internal node behavior

Description

Since many types of messages and supplies are transferred in an ICS, we tested the implementation of a reactive algorithm to generate different types of messages and resources according to the severity of the event. We also used the algorithm to modify the node capacity at runtime according to fixed rules between the federal, state and local levels.

Conditions

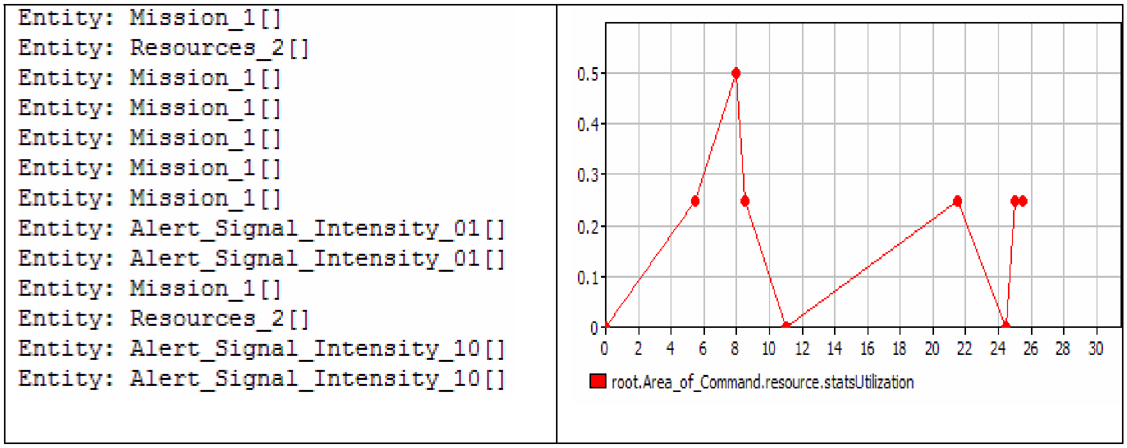
By mean of community of states to modify at run time the internal parameters in the node named *Incident_Commander* such as; type of messages, number of resources, delay time and queue priority.

Conclusion

The results showed that a hybrid model is well situated for simulating structured and non-structured data according to fixed distribution of probabilities identified in real command and control systems. Nevertheless, it is necessary to create an intelligent mechanism to follow the sequence of the data and resources throughout the components of an ICS.

The traditional discrete applications based on queues and servers can be enhanced by means of community of states but validated experiments are required for supporting the models.

Figure 53a shows a set of passing messages, generated in the logger of the internal *Incident_Commander* structure. The types of messages are modified by a signal received from the either federal or state levels. Figure 53b shows how change the utilization of resources after receiving signals of the either federal or state levels.



(a) (b)

Figure 53: (a) Logger messages passing; (b) Dynamic utilization of resources

Experiment 5: Gathering longitudinal matrices of connections and testing the dissemination of data and resources in the digraph

Description

Most of the time, an extreme event interrupts the physical infrastructure of an emergency organization and produces modifications in the dyads relationships of an ICS. In other cases, due to event evolution, new nodes are incorporated into the ICS, modifying the digraph and eventually producing a change in the role and position that each node plays in the emergency system. The dyads relationships were fixed in accordance to the adjacency matrix (Appendix B), and mechanisms were tested for simulating the dynamic changes of the connections at runtime. We tested the diffusion of entities in the system by means of *alerts* sent by the node *Sensor* to the node *Hospital 1 A*. The dissemination of the flows of data in the ICS was collected at different points in time.

Conditions

For collecting the longitudinal digraph we tested the mechanism of states of transition which allowed triggering several methods for controlling the interaction of the nodes. When the node n_i was connected with the node n_j, the adjacency matrix must show a number *1* in the position *i,j*. On the other hand, when the methods of control disconnected the association in the position *i,j*, the adjacency matrix must show the number *0*. The disconnection or connection of the nodes was made by closing or opening the ports of the objects.

In order to analyze the dissemination of data and resources in time, we collected entities transferred in the ICS digraph at times 5, 15 and 30 units.

Conclusion

The simulation of the adjacency matrix presented three main problems of design and implementation:

- The mechanism of states of transition was well situated to control the states of the ports of a small portion of established connections in the digraph. Nevertheless, an intelligent algorithm is required to control up to *n(n-1)* connections in the digraph. Moreover, the mechanism of control was not prepared to generate new connections at runtime, additional research will be necessary to deal with this issue.
- The states of transition could manage the connection between existing nodes, but they were not designed to generate new nodes at runtime in the ICS digraph. The methodology will require the incorporation of new nodes at execution time.
- Once the model was run, the flows were transferred between the source nodes and the receptor nodes, nevertheless when the connections were interrupted the flows remained in

the system and the entities were fed by other nodes. It is required that additional research be conducted for dealing with this problem.

Table 38 shows the evolution of the dissemination of data and resources in the digraph at times 5, 15 and 30 units.

Table 38: Dissemination of data in the ICS at different point in time (number of messages)

Node	Closeness In	Closeness Out	In Deg.	Out Deg.	Time = 5 units Flow	Total	Time = 15 units Flow	Total	Time = 30 units Flow	Total
1.Federal Gov.	0.42	0.44	6	7	1	7	15	105	30	210
2.Multi Agency Coor.	0.42	0.33	7	4	0	0	5	20	10	40
3.Fed.Situation Map	0.36	0.39	5	5	2	8	5	25	10	50
4.HEMA	0.50	0.45	10	9	1	9	5	45	10	90
5.Transp. Agency	0.37	0.42	6	8	0	0	5	40	10	80
6.State Govern.	0.51	0.42	10	7	3	21	15	105	30	210
7.State Situation Map	0.48	0.55	8	10	1	10	5	50	10	100
8.State Evacuation	0.39	0.46	4	9	0	0	5	50	10	90
9.State HEMA	0.44	0.55	9	10	1	10	5	50	10	100
10.State Transp.	0.41	0.44	6	7	0	2	4	28	10	70
11.State National Guard	0.40	0.41	6	5	1	1	6	36	22	130
12.Mayor A	0.49	0.57	14	14	2	28	15	210	30	420
13.Industrial Plant A	0.31	0.35	1	4	0	0	1	4	3	12
14.Stadium/Arenas A	0.34	0.34	1	3	0	0	4	12	10	30
15.Airport Adm. A	0.35	0.37	2	2	0	0	5	10	10	20
16.Transport Agency A	0.37	0.39	5	2	0	0	2	4	10	20
17.Multi Agency A	0.42	0.41	6	3	0	0	5	15	10	30
18.National Guard A	0.29	0.41	0	3	0	0	0	0	0	0
19.Sensor	0.00	0.30	0	1	5	5	16	16	31	31
20.Private Org 1. A	0.34	0.32	1	1	0	0	5	5	10	10
21.Red Cross A	0.00	0.30	0	1	0	0	0	0	4	4
22.Hospital 1 A	0.35	0.42	3	3	2	6	5	15	10	30
23.ECall_ Center A	0.44	0.48	8	4	1	4	5	20	10	40
24.Police Depart A	0.44	0.45	6	4	0	0	15	60	30	120
25.Fire Depart A	0.43	0.45	5	5	0	0	15	75	26	130
26.Intelligence A	0.39	0.35	4	3	0	0	4	11	6	18
27. Risk Ass. A	0.39	0.35	4	3	0	0	5	15	10	30
28. Weather Inf. A	0.39	0.35	4	4	0	0	4	16	6	24
29. Incident Comm. A	0.57	0.53	14	13	0	0	15	110	30	420
30.Liaison Officer A	0.37	0.38	0	2	0	0	3	3	7	7
31.Area of Command A	0.39	0.40	4	5	0	0	15	75	30	150
32.Operations Chief A	0.39	0.37	2	5	0	0	13	13	24	24
33.Air Operat. Chief A	0.41	0.27	4	1	0	0	14	14	23	23
34.Heliport Resources A	0.40	0.22	2	2	0	0	5	10	10	20
35.Task Force A1	0.38	0.36	3	3	0	0	15	45	30	90
36.Wings Resources	0.43	0.22	4	2	0	0	6	13	21	42
37.Task Forces A2	0.38	0.36	3	3	0	0	15	45	30	90

We tested the correlation between the centrality measures (the first four columns) and the total number of entities transferred in the ICS at different points in time.

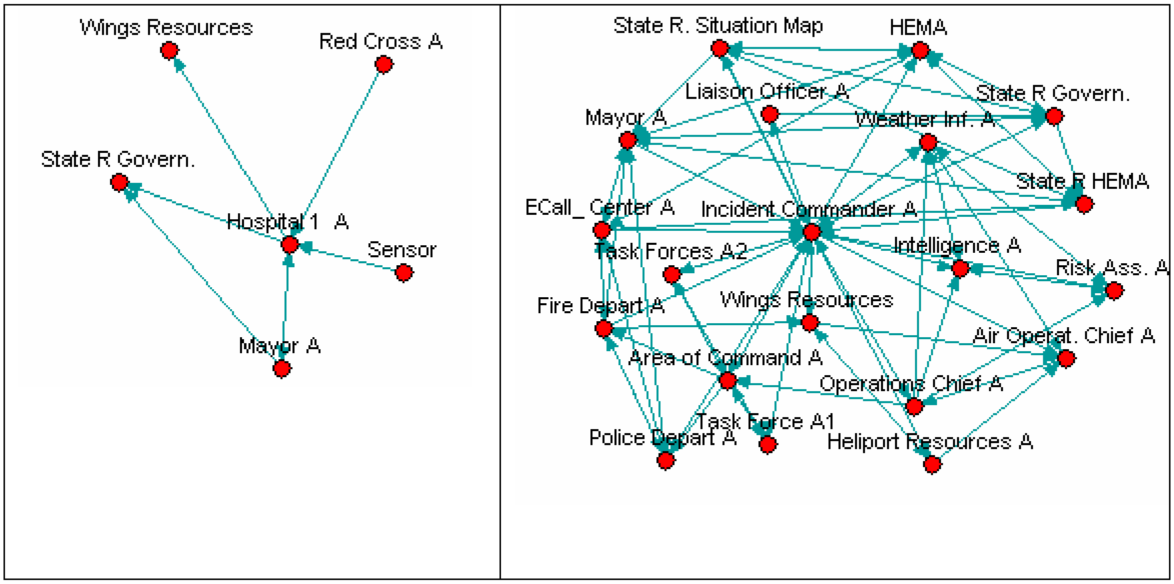
The Pearson correlation provided evidence that in time 5, the total number of flows generated in the ICS digraph has a linear relationship with the in-degree and out-degree indexes (see Table 39).

In times 15 and 30, the total number of entities generated by the node presents a linear relationship with the four centrality measures.

Table 39: Pearson correlation between centrality measures and total number of entities

	Closeness In	Closeness Out	In-Degree	Out-Degree
Total messages at time 5	0.273	0.521	0.614	0.595
p-value	0.102	0.010	0.000	0.000
Total messages at time 15	0.474	0.634	0.747	0.772
p-value	0.003	0.000	0.000	0.000
Total messages at time 30	0.501	0.626	0.789	0.794
p-value	0.002	0.000	0.000	0.000

The critical point in the analysis of Table 38 is the delay time in which the pieces of data arrived to the *Incident Commander* node (decision maker on site). Since the ego-digraph of the *Hospital 1 A* node does not include the *Incident Commander* and data must pass by other nodes before arriving to the main node on site. Figures 54a and b show both ego-digraphs.



(a) (b)

Figure 54: (a) Ego-digraph *Hospital 1 A*; (b) Ego-digraph *Incident Commander*

CHAPTER SEVEN: CONCLUSIONS AND FUTURE RESEARCH

Conclusions

In the literature review we identified a great deal of research and models for understanding how an organization performs its tasks in a collaborative environment. Nevertheless, most of the research and models have analyzed an organization from a static viewpoint, and only a few simulations have been built mainly over a discrete platform.

First hypothesis

In Chapter One we formulated as our first hypothesis that a hybrid simulation based on discrete simulation, system dynamics, and agent-based modeling is an adequate platform to represent the dynamic sequences produced in an emergency management organization. In Chapter Three, that hypothesis was associated with several technical questions that addressed this research and whose answers are summarized below.

What features of an emergency response organization are possible to simulate in a network centric environment?

By analyzing five cases of extreme events, we determined that most of the time an emergency organization has a well defined plan based on procedures and alarms, and some more-developed organizations have an ICS.

It was demonstrated that there exist tools for analyzing the patterns of the dyadic and triad relationships that are formed in an emergency management system.

We established that if the *digraph* presents enough nodes, then it is possible to obtain significant metrics from its adjacency matrix and to contrast those results with known behavior of random and scale free *digraphs.*

If data is available, then the initial model of the dyads relationships can be modified by mean of *community of states,* and new measures of performance might be collected.

From a continuous perspective, it was shown that extreme events that have a constant development over time can be modeled and simulated using a set of continuous variables, and events that are carried out in specific periods of time might be modeled as a combination of discrete and continuous variables.

By using a mechanism of control (agents), we showed that the extreme events can be either stochastically or deterministically managed for impacting one, a set, or the whole organization, thus permitting us to analyze the chains of command and sequence of procedures based on the dyadic interrelationships of the *digraph.*

Finally if cognitive models exist, they can be incorporated as objects (agents) into the internal configuration of the nodes and testing their influence in the whole *digraph* behavior.

<u>Is there a more suitable simulation technique for modeling the interactions among the nodes in a networked scenario? (Testing best candidate simulation technique)</u>

Throughout this research we have maintained that interactions imply the study an emergency organization in three forms: static, evolution, and dynamic flows. We tied those interactions to the three types of data defined in Chapter Three: semantic, qualitative and quantitative data.

We used a static simulation technique based on the Markov Chain Monte Carlo (MCMC) method for comparing the topology of several emergency organizational structures. We suggested that this technique is an invaluable help for future research in this field, especially when data stored in the command and control system is available for analyzing the initial deployment of an organization. Based on the five cases of study, our findings suggest using *semantic and quantitative* data for evaluating the static organizational configuration.

We demonstrated that the evolution of the interactions, analyzed as changes in the dyadic contacts between nodes, requires the inputs that provide the SD models for representing either an extreme event or the team performance in the nodes. Nevertheless, it will be necessary to use a mechanism of control, based on *community of states,* for regulating those interactions. The timing with respect to how the *digraph* evolves requires *quantitative data* stored in the database of a system.

The dynamic interactions of the dyads are discrete entities, which can be modified during the simulation execution in accordance with the different types of messages, tasks, decisions and resources that are transferred in an emergency organization.

We tested the SD technique for modeling the interaction among the nodes, and even though the eigenvalue analysis of the linearalized matrix $\boldsymbol{A}$ in the system $\boldsymbol{dx/dt = AX+ b}$ provides good insight regarding the loops that contribute more to the system behavior, this technique presents three main problems for modeling a huge networked scenario. The first is that it does not allow modification of the flows between the dyadic interactions and a modeler is restricted to use only one type of entity. The second is that the number of feedback loops in the networked scenario might increase dramatically at certain periods, which makes it impossible to mathematically analyze the system's behavior (Kampmann, Table 23, Chapter Five). The third problem is the null capacity of the variables of state (levels) for modeling the internal behavior of the nodes (We propose an object oriented approach to model a complex internal behavior).

Nonetheless, we demonstrated that an isolated SD model is well situated for performing reduced analysis of part of a *digraph*, such as in the study an ego-net (sub-graph of a focal node) and the behavior of its variables of states.

Therefore, the four simulation techniques are suitable for modeling different components of a networked scenario, but a discrete approach is suggested for transferring entities among the nodes.

<u>How could several simulation techniques work together in a networked scenario?</u>

We demonstrated that SD and DES techniques are suitable for modeling several features in a networked scenario that represents the three domains – physical, information and cognitive – but most of the time an agent mechanism will be required for controlling the relationships between both. That mechanism was named *community of states.*

<u>How could a model enhance its usefulness when it is combined with graph theory and social network analysis?</u>

In the simulation community, no previous research efforts have merged discrete event simulation technique with graph theory and social network analysis, and only a few applications were identified in the field of continuous simulation for understanding the feedback loops of a system.

We argue that graph theory and its interpretation by mean of social network analysis provide tools for improving the structural analysis and future design of complex systems, especially when there are social interactions into them. An ICS and an EOP are social systems supported in network centric technologies, and in accordance to our findings, the topology and interactions of those systems should be modeled with a combined approach of simulation techniques, graph theory, and social network analysis.

Is it possible to combine team performance with flows and tasks carried out by nodes in a network centric scenario?

Yes, it was demonstrated in two ways: continuous variables that are passed as parameters of the discrete objects or by using states of transition technique.

What mechanism of control could a modeler use for controlling a hybrid simulation?

It was demonstrated that our definition and implementation of *community of states* is an effective mechanism for controlling the whole hybrid simulation.

Can the hybrid simulation be validated for predicting performance of an emergency organizational structure?

Additional research, surveys, and data analysis of databases will be necessary for validating and predicting performance in organizational structure.

Second hypothesis

In the second hypothesis we stated that a hybrid simulation can be combined with social networks analysis and linear programming in order to assess the evolution of an organizational structure over time, and this type of simulation is suitable for detecting bottle necks, quantification of reaction time, loading jobs, vulnerabilities, priorities, and synchronization, among other measures of performance. This hypothesis was tied to the following operational questions:

<u>What social network metrics are more significant for designing and evaluating an organizational structure in a network centric scenario?</u>

The analysis of complex networks is a novel area, and few research efforts have been conducted focusing in organizational network behavior. Most of the current findings have been developed in the analysis of the World Wide Web, chemical analysis, and social interactions. Recently, Care (2005) formulated a similar question in the military arena: "If we could choose the type of combat network we should design, what properties should it possess?" He defined some of the more useful network properties and recommends values for combat networks. The previous statement provides orientations to this research to concentrate the analysis in the desired properties of the *digraph* that represent an emergency configuration, and we added that those properties are determined by the types of threats that an organization must face in a network centric scenario.

For instance, using the social network classification in Chapter Four, if a community foresees that a local threat might quickly affect the whole local ICS, an ego-net analysis focused on selected nodes could likely be more useful for improving the readiness of the organization. On the other hand, if the event will affect a broad area and requires a collective and coordinated reaction of the whole ICS, the analysis should probably focus in the set of centrality and connection measures.

Does the *digraph diameter* increase or decrease in an organizational structure when it faces an extreme event?

Based on the analysis of theoretical *digraph* and the five case studies (Appendix A and B), we found qualitative and quantitative evidence that the "network diameter" increases when a organization faces an extreme event, (we demonstrated that the removal of the *Hospital* node breaks up the digraph in three disconnected components), but experiments with real data will be necessary to confirm this issue. The increment of the digraph diameter will be a function of vector event defined in Chapter Three and the evolution of the three domains in the networked scenario.

How can the position and performance of a node in the digraph determine the behavior of the whole organization?

We demonstrated that the influence of a node in the ICS digraph will depend on its topological position and the role performed in the organization. For instance, nodes with low score in degree centrality could control the whole behavior of an ICS if their tasks are not accomplished. On the other hand, the dyads work by mean of interactions, and those are a function of the internal behavior of the nodes, thus insufficient measures of performance in a node could alter the complete performance of the *digraph*.

Contributions and future research

By means of the verification of both hypotheses and their associated questions and answers, this research provides a hybrid methodology that combines the three main simulation paradigms with a social network analysis based on graph theory.

The application of this methodology to a complex social system, such as an ICS, provides significant insight for understanding how to design and evaluate an organization in the three defined domains: physical, informational, and cognitive.

Some might argue that the models used are not representative of the three domains, in which case the proposed methodology is still valid for incorporating other models in the object oriented approach.

Thus, we have used the principles and implementations of the main simulation techniques over only one architecture, and the measures of performance, results, and data yielded in the model can be analyzed with the classical tools of discrete simulation, system dynamics simulation, and social network analysis.

Further, the methodology can be applied to other less complex systems that require the incorporation of a richer approach beyond of an individual either discrete or continuous simulation.

By analyzing a networked scenario whose data is available, significant experiences and results can be obtained from a synthetic environment, and these experiences and results can be used to improve the configuration of the real system that is managed by human beings.

Though the system composed by humans beings and machines are difficult to validate, when previously established procedures exist, they can be tested for detecting vulnerabilities and metrics regarding loading jobs, time delays, sequences, message distribution, etc.

In order to continue improving this methodology, we have identified four areas for future research:

- Developing an intelligent internal behavior of the nodes, in accordance with the role that they play in the context (cognitive models). So far, we have showed that as messages flow through the organization replicating the flows of a chain of command, at certain periods the nodes change the types of data sent to others nodes, emulating different information such as decisions taken, missions for carrying out, tasks, or ordinary communication. An internal node behavior should incorporate a semantic analysis of the data sent by other nodes and make decisions based on this information. For instance, that data might provide information regarding the severity of the extreme event and the nodes processing this data in accordance to set rules. Notice the strong relationships of this future research for modeling and simulating an organization with the current research in semantic analysis of the data stored in the real systems based on information technology.

- We suggested a set of significant metrics for analyzing an emergency organization, but it required more research in the database for identifying the metrics ranges in which the organization works better in accordance with the type and location of the extreme event, and those ranges can only be found out by means of an extensive collection of data and simulation experimentation.
- In order to simulate a longitudinal network, the mechanisms of incorporation of new actors to the *digraph* and the interruption of the contact among the nodes must be validated. These challenges will still be without solution if data is not available for determining the required patterns that govern the contacts among the nodes.
- Experimentation is necessary in order to find out if the hybrid model could support an *after action review* and if it is simple enough to be used by decision makers and stakeholders for improving their ICS and EOP.

APPENDIX A: DISASTER ANALYSIS

Oklahoma City Bombing, USA

These features were interpreted and summarized mainly from the following documents:

- Case study that identified the information and communication flows affecting the response to the April 1995 bombing of the Murrah building. (MIPTS, 2006).
- Oklahoma City-Seven Years Later. (MIPTS, 2006).

The extreme event	On April 19, 1995, a large bomb exploded in front of the Murrah Federal Building in Oklahoma City. As a consequence of the explosion, 167 people died.
Features for modeling	*Information flows and resources flow.* Research and reports identified information issues from a narrative perspective. Critical information and critical resources used were not clearly shown and are mentioned in qualitative way. Many situations were described regarding connections among first responders (fire fighters, police officers, and others). The reports also consider how the federal, state, and local levels were involved in the extreme event. Nevertheless, the information available do not contain timing, quantitative data and location of actors. *Disaster planning*. Disaster planning must address internal communication requirements. The command post was implemented on time, but it must be assumed that this facility will be on scene within days, and then it should be put in a safe area. In the future, media must be incorporated into disaster response plans. The command post must have a plan to anticipate donations and volunteers. *Communication system.* As a result of the event, capacity and integration of communications systems were critical to a successful response. There was not physical damage to the telephone system but after the incident the demand for service overwhelmed the network. The problem of frequency in communication systems could have been solved using media broadcast. *Situation awareness.* The difficulty of conveying and sharing information among responders was proportional to the physical size of the response area. The lack of standard formats did not allow using Internet as an element to share data and information. *Interoperability.* Some inefficiency was produced by the lack of interoperability between radio equipment of Oklahoma City Municipal, the state and county and the federal agencies. The agencies and responders used different acronyms (according to their

	knowledge) which inhibited a clear communication. *Human Factors.* People were working until they were ready to drop. Multiples studies have shown that judgment begins to erode after a person has worked 12 hours. For future events it was recommended to deal with this problem. *Chain of Command.* In future extreme events, the incident commander and his staff could improve their coordination if plans have been made and practiced in training systems. The sequence of the tasks and orders in the chain of command and local decision making were documented from a qualitative perspective. There are no quantitative data. It was identified that the coordination among the Governor, the State Director of Management, the Mayor and other agencies was critical to direct resources such as Police and National Guard. Future events require working with telephone service providers to gain additional capacity in the incident command chain.
Classification for modeling	Local extreme event, there were no posteriori events and it affected only a specific place. The authorities were involved in the problem gradually.
Lesson Learned	Many highly detailed studies were made, but with focus on a single aspect. There are no quantitative data available and no study considers this issue. After action review showed that "planning" emerged as the most significant factor for responding to this type of extreme event, every community should have and test their plan. It was concluded that reinforced behavior by using a training methodology is the key issue for keeping the community prepared to face a new event.

<u>Kobe Earthquake, Japan</u>

These features were interpreted and summarized mainly from the document:

- Lessons Learned from the Kobe Earthquake (Tierney, Goltz, 1997).

The extreme event	On January 17, 1995, a devastating earthquake struck the cities of Kobe, Nishinomiya and Ashiva in Japan; immediately numerous fires began in different places; a total of 6,279 people died.
Features for modeling	*Information flows and resources flow.* After action analysis found many delays in the mobilization of critical resources and the initiation of key response tasks due to lack of situation awareness. The resources of the Self Defense Force (SDF) were not initially mobilized until nearly 24 hours after the earthquake, because military forces were not well-linked to local preparedness efforts and did not participate in disaster drills and exercises.

	Disaster planning. Federal legislation provided an overall structure for planning and response, but local governments had the primary authority for disaster management. Each prefecture and local jurisdiction had a Local Disaster Prevention Council (LDPC) that is responsible for the development of area-specific disaster plans. *Communication system.* An accurate situation assessment was impossible due to the disruption of communications and transportation networks. *Situation awareness.* The interferences of communication systems and the magnitude of the damage to buildings and roadways made early situation assessment difficult. Loss of back-up power for key emergency functions increased the confusion. *Interoperability.* Some jurisdictions established close links with emergent groups, while others officially recognized their existence but engaged in only limited coordination, and still others allowed newly-formed volunteer networks to operate but avoided official contact with them. *Human Factors.* Local officials in Kobe City and Hyogo Prefecture were initially unaware of the magnitude of the disaster because of major communications problems and traffic congestion that made movement difficult throughout the impact area, and because so many emergency responders and public officials were also disaster victims. *Chain of Command.* Due to lack of effective communications links and accurate information from the impact area, the government failed to comprehend the severity of the situation for a number of hours and consequently was slow in committing needed resources.
Classification for modeling	A regional extreme event, there were many posteriori events as consequences of the initial earthquake, such as fire, explosions, and gas leaking. Authorities were involved gradually in the event.
Lesson Learned	The Kobe earthquake highlighted the importance of obtaining and disseminating information, particularly in the immediate aftermath of a major earthquake or other disaster.

Hurricane Mitch, Central America

These features were interpreted and summarized mainly from the document:

- Hurricane Mitch. (U.S. Army Peacekeeping Institute,1999)

The extreme event	In October 1998, Hurricane Mitch, category 5, hit the coast of Central America, with wind at 208 miles an hour. This event caused more than 18,000 deaths.
Features useful for modeling	*Information flows and resources flows.* Immediately after the event there was extensive international cooperation. Many type of supplies arrived to Central America, but their distribution was affected by lack of a centralized logistic control. Many authorities were in charge of various things at various times. Feedback into the planning process was not structured, and many teams, agencies and volunteers formulated the question: "*What is the Process?*" *Disaster planning.* Military and civilian coordination in the operations did not include civilian agencies, International Organizations (IOs), Non-Governmental Organizations (NGOs), or relevant Host Nation civilian and military organizations. *Communication system.* The communications, methods and means of operation and command and control between the various military and civilian components were disconnected. *Situation awareness.* Lack of unity of effort and a corresponding strategic and operational planning process. "People did not know each other and did not know what another organization could bring to the table and how". *Interoperability.* Primary recommendations center on the need to clearly define civil-military authority relationships and supporting and lead roles that, once defined, can and will generate an effective interagency and multinational unity of effort. There was a duplication and triplication of effort by lack of coordination. *Human Factors.* Effectiveness and ultimate success in humanitarian assistance and disaster relief operations depend on educational as well as organizational solutions. Doctrine was inadequate to meet the requirements of complex multinational, multiorganizational, and multidimensional humanitarian emergency situations. *Chain of Command.* Planning and implementing procedures did not work well. This issue was considered to be, at its base, a command and control problem.

	Consensus was that pervasive ad hoc planning and implementing were impeded by a recurring question of "Who is in charge?" Because of a certain lack of clear authority lines and well-defined lead and supporting roles, each major actor tended to "do his own thing" and stay within his own "stove-pipe" organizational structure.
Classification for modeling	The extreme event involved various countries; there were many local, international, private and military organizations which participated by several months.
Lesson Learned	There was no multinational doctrine or multinational standard for dealing with this type of extreme event. Force protection was required in areas where the law and order have been broken. It was necessary to ensure a proper balance between force protection and operational flexibility. Failures in planning, command/control and organizational structure produced problems of coordination. It was identified the necessity of mechanisms and processes for the purpose of creating viable models that integrate vertical and lateral planning and implementing processes.

Chernobyl Nuclear Disaster, Chernobyl, Ukraine

These features were interpreted and summarized mainly from the documents:

- Assessment of Radiological and Health Impact. (Nuclear Energy Agency,2002)
- The Chernobyl Disaster Its effect on Belarus and Ukraine. (Mitchell, 1996)

Extreme event	On April 25 -26, 1986, a nuclear power accident occurred at Chernobyl, Ukraine. The nuclear power plant located 80 miles north of Kiev had 4 reactors and, whilst testing reactor number 4, numerous safety procedures were disregarded. At 1:23 am the chain reaction in the reactor became out of control, creating explosions and a fireball which blew off the reactor's heavy steel and concrete lid. The Chernobyl accident killed more than 30 people immediately, and as a result of the high radiation levels in the surrounding 20-mile radius, 135,000 people had to be evacuated.
Features for modeling	*Information flows and resources flow.* Because there were no nearby hospitals that could treat radiation patients, some were taken to one hospital in Kiev, and the most severely burned were transported by plane to Moscow, the only city in the country adequately prepared for such an emergency. *Disaster planning.* According to the initial reaction of the authorities it was clear that they were unprepared for an accident, and they had to make decisions as the accident

	evolved based on criteria that could have been established beforehand. *Communication system* As the event was clearly located and it spread out gradually, the critical infrastructure did not fail, but the kind of information transmitted did not allow the authorities to evaluate the severity of the incident. *Situation awareness.* Chernobyl was an object lesson in spontaneous and disorganized response to a major crisis. The distribution of information was limited and the severity of the consequences allowed to the authorities realized of the magnitude of the disaster. *Interoperability* Many organizations were involved in the decision making, as no clear –cut demarcations had been agreed and established. *Human Factor.* After the explosion, fire crews succumbed quickly to the effects of intense radiation. Helicopter pilots who attempted to blanket the fire with sand and chemicals also died, usually weeks or months later. *Chain of Command.* It was suggested a lack of personnel specialized as staff in the chain of command, it delayed the process of make decisions increased the severe consequences of the extreme event.
Classification for modeling	An abrupt event that involved quickly all the levels of emergency response. The consequences of the event were still around after months, and years.
Lesson learned	Since the disaster involved several countries, at that time there was not a standard system for communicating the problem beyond the country in which in event happened.

Hurricane Katrina

These features were interpreted and summarized mainly from the documents:

- The Federal response to Hurricane Katrina. Lesson learned (Federal Review, 2006)

Extreme event	On August 23, 2005, the most destructive natural disaster hit the Gulf Coast in Mississippi, Louisiana and Alabama. As consequence over 1,300 people died, thousand were evacuated and the city of New Orleans and other coastal communities suffered irreversible structural damages.
Features for modeling	*Information flows and resources flow.* "The existing planning and operational structure for delivering critical resources and humanitarian aid clearly proved to be inadequate to the task". "Throughout the response, Federal resource managers had great difficulty determining what resources were needed, what resources were available, and where those resources were at any given point in time". "There was no effective mechanism for efficiently integrating and deploying these resources". "FEMA's lack of a real-time asset-tracking system, left Federal managers in the dark regarding the status of resources once they were shipped". *Disaster planning.* The process for decision making was supported by the best emergency system, ever before designed, analyzed and documented for facing an extreme event. The National Incident Management System (NIMS) provides a common approach for Federal, State and Local government and develops and administers an integrated National Response Plan (NRP). There was a national response plan adopted to establish a single framework for managing domestic incidents. Nevertheless the incident systems do not "provide the necessary framework to manage the challenges posed by 21st Century catastrophic threats and the new plan created by the federal government since the terrorist attacks on September 11, 2001 failed to adequately account for widespread or simultaneous catastrophes". "At the most fundamental level, part of the explanation for why the response to Katrina did not go as planned is that key decision-makers at all levels simply were not familiar with the plans". *Communication system.* "Hurricane Katrina destroyed an unprecedented portion of the core communications infrastructure throughout the Gulf Coast region". "The storm debilitated 911 emergency call centers, disrupting local emergency services". "Many available communications assets were not utilized fully because there was no national, State-wide, or regional communications plan to incorporate them". "DOD brought robust communications infrastructure, logistics, and planning capabilities".

	Situation awareness. The specific triggers for the NRP were unclear and it was found lack of clarity regarding when and how an event becomes an Incident of National Significance. In the federal level "lacked real-time, accurate situational awareness of both the facts from the disaster area as well as the on-going response activities of the Federal, State, and local players". "FEMA requested assistance from DOD without knowing what State National Guard forces had already deployed to fill the same needs**".** *Interoperability* The Incident Command System (from NIMS) was the mean by which all the actors should have coordinated their effort and eliminated duplication of tasks. Likely the most important issue in NRP is the "concept of operation" applied in Hurricane Katrina. Concepts, principles and terminology might have provide a clear coordination and effectively. At that time," Federal, State, and local governments had not yet completed a comprehensive strategy to improve operability and interoperability to meet the needs of emergency responders. This inability to connect multiple communications plans and architectures clearly impeded coordination and communication at the Federal, State, and local levels." *Human Factor* There was a clear incident management protocols and procedures for all levels, for instance was reported: " JFO staff and other deployed Federal personnel often lacked a working knowledge of NIMS or even a basic understanding of ICS principles". *Chain of Command* "Command centers in the Department of Homeland Security (DHS) and elsewhere in the Federal government had unclear, and often overlapping, roles and responsibilities".
Classification for modeling	Event that involved simultaneously all the levels of the emergency management organization. The evolution of the extreme event enables a modeler to simulate of the emergency organizational structure behavior before, during and after of the Hurricane, nevertheless it is required to process the data stored in the database of the either the command and control systems or the communication systems.
Lesson learned	Four critical deficiencies in the national preparedness were reported: **1.** The processes for unified management of the national response. **2.** The command and control structures within the federal government. **3.** The knowledge of the preparedness plans. **4.** The regional planning and coordination.

APPENDIX B: ADJACENCY MATRIX

	F	M	M	H	T	S	S	S	S	S	S	M	I	S	A	T	M	N	S	P	R	H	E	P	F	I	R	W	I	L	A	O	A	H	T	W	T
Federal Gov.	0	1	1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Multi Agency Coordina	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fed.Situation Map	1	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEMA	1	1	1	0	1	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp. Agency	1	1	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
State R Govern.	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
State R. Situation Map	0	0	1	1	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
State R Evacuation	0	0	1	1	1	1	1	0	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
State R HEMA	0	1	0	1	0	0	1	1	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
State R Transp.	0	0	0	0	1	0	1	0	0	0	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
State R National Guard	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mayor A	1	1	0	1	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0
Industrial Plant Adm. A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Stadium/Arenas Adm A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Airport Adm. A	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transport Agency A	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Multi Agency Coor. A	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
National Guard A	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sensor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Private Org 1. A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Red Cross A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hospital 1 A	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
ECall_ Center A	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Police Depart A	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0
Fire Depart A	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0
Intelligence A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
Risk Ass. A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0
Weather Inf. A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0
Incident Commander A	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
Liaison Officer A	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Area of Command A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	1	0	1
Operations Chief A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0	0	0
Air Operat. Chief A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Heliport Resources A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Task Force A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1
Wings Resources	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Task Forces A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0

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