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Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments

Abstract

Achieving efficiency in coordinated action in rapidly changing environments has challenged both researchers and practitioners. Emergency events require both rapid response and effective coordination among participating organizations. We created a simulated operations environment using agent-based modeling to test the efficiency of six different organizational designs that varied the exercise of authority, degree of uncertainty, and access to information. Efficiency is measured in terms of response time, identifying time as the most valuable resource in emergency response. Our findings show that, contrary to dominant organizational patterns of hierarchical authority that limit communication among members via strict reporting rules, any communication among members increases the efficiency of organizations operating in uncertain environments. We further found that a smaller component of highly interconnected, self adapting agents emerges over time to support the organization's adaptation in changing conditions. In uncertain environments, heterogeneous agents prove more efficient in sharing information that guides coordination than homogeneous agents.

Keywords: Agent-Based Simulation, Emergency Management, Network Evolution, Performance

Introduction

1.1   Vivid images of helpless victims from the Tsunami of South Asian countries, 2004, and the devastated New Orleans due to Hurricane Katrina, 2005 in the U.S. compelled policy makers and citizens alike to focus on improving efficiency in coordinating multiple organizations operating under extreme conditions (Comfort 2006). While participants in disaster response activities agree that they have to share information and work together, such a cooperative relationship is never easy to achieve. Emergency response organizations have their own organizational structure developed over years, but the structure is not necessarily designed to expedite interorganizational cooperation. Under tight time constraints, at issue is whether agents engaged in emergency response are more efficient when they conduct their own information search with the possibility of missing some aspect of the situation, or when they receive direction from an unchallenged authority that may not be on site and may not have complete information. Action is directed by those organizational units with higher authority that are presumed to have greater knowledge or experience in the field. The supporters of the hierarchical command and control structure argue that the coordination and efficiency can be achieved through structure. In contrast, we also expect that the tension between efficiency and coordination escalates in emergency environments under conditions of high uncertainty. Regarding efficient interorganizational communications to support information sharing and coordination, we consider seven propositions, as follows.

- Organizations design communication processes among their members as a means to control performance at specified levels of efficiency (Scott 2003)
- Organizations establish different types of authority relationships at different scales of operation that constrain their members' access to information (March 1999)
- Self organization requires sufficient structure to hold and exchange information, but sufficient flexibility to adapt to new conditions (Kauffman 1993)
- Emergency response personnel act within the limits of available information (Weick 1993)
- Within these limits, response personnel depend upon timely communication with external agents to inform their actions in dynamic environments (Comfort and Sungu 2001)
- Organizations operating in hierarchical environments reduce their capacity for coordination in uncertain conditions by structuring information processes that limit access to information among their members (Graber 2002)
- Organizations operating without constraints on communication or access to information tend to form scale-free networks that perform more efficiently than hierarchical organizations (Barabási 2002)

1.2   We explore these propositions through computational simulation (Carley and Prietula 1994 ; Gilbert and Troitzsch 2005). The simulation tries to imitate actual emergency response in the following aspects: incremental but random change of demands, organizations assigned different capacity in different jurisdictions, hierarchical structure within an organization, limited information search capacity of each agent, changes in ties of communication networks among agents. We explore six different communication patterns among organizations. Our focus is on daily operations of the emergency services with no major or catastrophic incidents modeled. Using the simulation, we analyze 1) which communication patterns are more efficient in responding to demands, and 2) how information exchange networks evolve through the interaction of agents.

Modeling Framework

2.1   Our modeling framework consists of two major components: organizational and spatial. The organizational component of our simulation framework models the hierarchical structure and the flow of information within these hierarchies. There are five organizations in the simulation and they correspond to police, fire, emergency medical services, public works and utility companies. We assumed a hierarchical pattern of authority for each type of organization with three levels of agents: street level agents (we call them agents), managers, and the single executive officer. An agent is capable of moving through the map and searching for demand or directly moving to an assigned demand site. Each agent can move only one cell during one unit of simulation time, but it can gather information about demand from a wider range of neighboring cells. This range can be interpreted as the amount of information available to a single agent and consequently for the organization as a whole.

2.2   Although the agents are information gatherers and immediate responders, decision making is not their role. Each agent is obligated to pass its

information to its manager and does not take spontaneous actions. The algorithm for the agent's decision making procedures is outlined in Figure 1. If a street agent has been assigned an incident, it goes directly to respond to the demand. If the agent has no assigned incident, it searches the area for possible demands. If any demand is spotted, the agent reports the incident to the manager. However the agent does not take any action until it receives a direct order from the manager. The manager assigns and coordinates the agents' actions within the jurisdiction. In terms of information flow, the manager interprets incoming information from different sources such as agents, other managers (when this option is allowed), and the organization's executive. The executive's role is supervising all managers for one organization and facilitating communication between them.
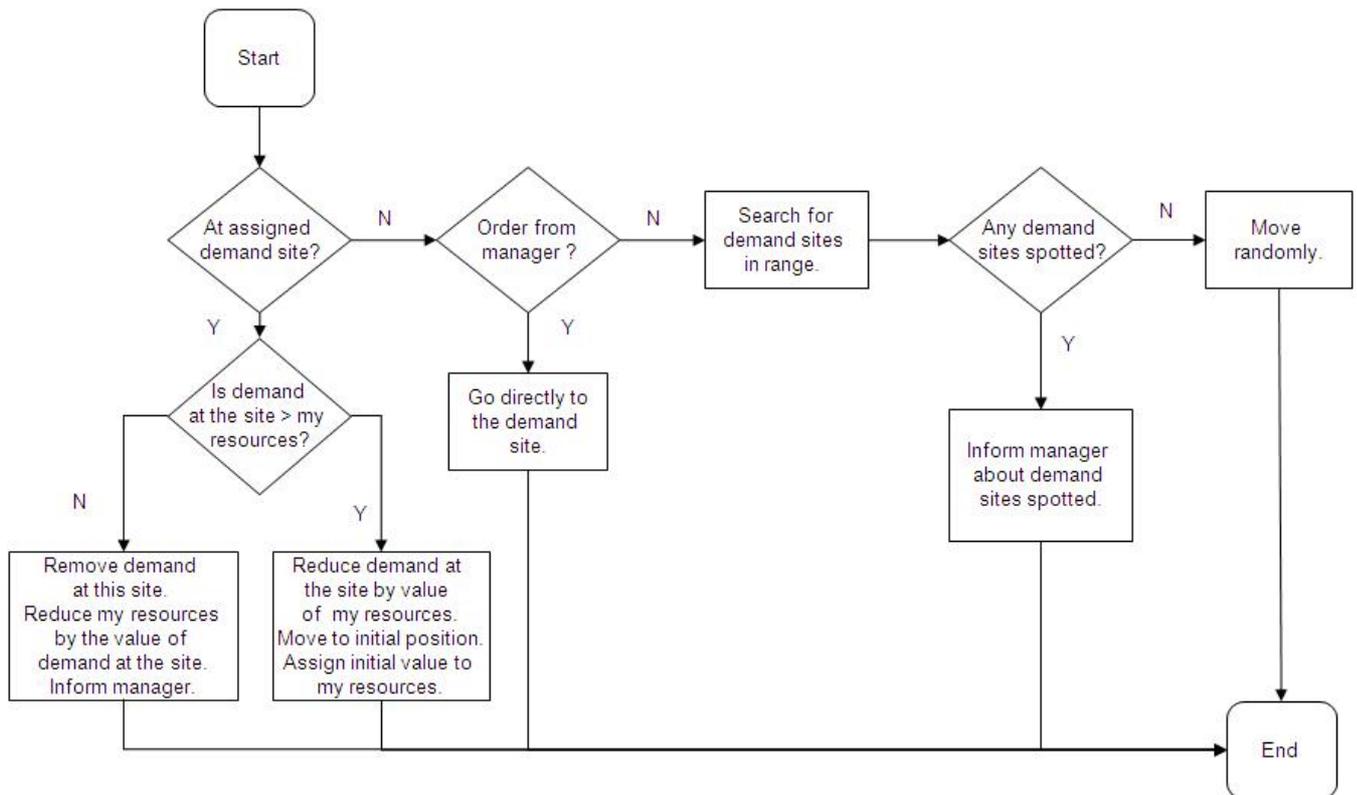

Figure 1. Street level agent's decision process

2.3   We assume all organizations have the identical structure. The information flow between organizations changes, while the decision making remains hierarchical for all conditions. During simulations we control the flow of information at three levels: between agents, between managers and between executives of different organizations. At the executive and managers' levels, we simply allow or prohibit communication. Establishing a communication link between two agents is more complicated. Two agents can exchange information only when they have met at the demand site in the past. This action can be viewed as establishing an individual's professional network. When two agents from different organizations meet at the event site, they can establish (with some probability p) a professional contact. The agents' social network is created in this manner. Although the agent is obligated to report any observed demand to its manager, it can spontaneously inform colleagues from other organizations by overriding the formal communication channels.

2.4   In our model, we account for delays related to communication and decision processes. We assume that it takes one unit of simulation time to pass a message between two agents and the same unit of time to pass an action request.

2.5   To reflect the limits of the information process, we impose different restrictions on the range of information search and maintenance of the relationship. For instance, agents can search a limited neighboring area, and ties among agents fade out if they do not interact for a long time.

2.6   In our experiments, we used 6 communication patterns between organizations. These patterns are presented in Figure 2. For convenience we use three letter acronyms to denote them. The three letters correspond to the three levels at which communication between organizations can take place: executive (E), managers (M), and agents (A). If communication is prohibited at a given level, we denote it by 0. For example, EMA denotes that communication at all levels is allowed, while 00A describes communication permitted only among the street level agents.

2.7   To explore these patterns, we created a computer based simulation. For each set of initial conditions, we tested the six communication patterns. As a measure of the effectiveness of response to demand, we used the mean time from occurrence of the event to the moment when its demand is entirely cleared over all demand sites that were engaged during the simulation.
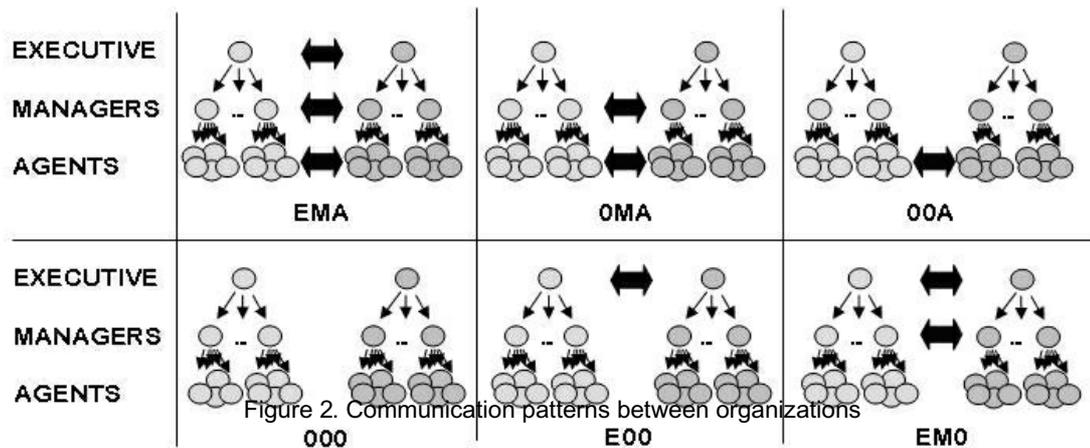
Figure 2. Communication patterns between organizations

2.8   One challenge was to ensure that the simulation behaves in a stable manner - that is, agents manage demand so the amount of demand never grows with time. After an initial fluctuation, demand stays at some stable level. Too little demand would cause a large majority of the agents to be idle and lead to insignificant results. The demand function of the simulation should be chosen so that agents are reasonably busy, but not easily overwhelmed. This is consistent with the situation that exists in real emergency response systems. On a daily basis, response organizations work at an average of 20% of their maximum capacity, resulting in the remaining 80% being in reserve for additional emergencies[1]. To determine an appropriate demand function, we relied on data from the documented distribution of actual incidents. We identified 5 major types of incidents based on an earlier analysis of incident data from the Pennsylvania Emergency Management Agency's (PEMA) Morning Reports (2003). The 67 county emergency managers in Pennsylvania are required to report the number, type, and severity of emergencies that occurred in their jurisdictions on the previous day to the state agency, PEMA. These daily reports offer a statewide source of data for identifying trends, types of incidents, and unusual demands on emergency service organizations for Pennsylvania.

2.9   The five major types of emergency incidents reported for Pennsylvania in the Morning Reports include: fire, transportation, utility, hazardous materials (HazMat), and explosion emergencies, moderate events that disrupt normal operations in a community. Each of these incident types has unique characteristics in terms of frequency and severity of events. We used these results to model the occurrence of incidents. The findings show that the severity of the incidents follows the lognormal distribution, and the time between incidents follows the exponential distribution with unique parameters (see Figure 3). Each incident type is translated into demand on some organizations as defined in Table 1. For example, a hazardous materials event requires intervention by the fire department, police department and emergency medical services agencies. From these empirical data, we model demand functions for each incident type.
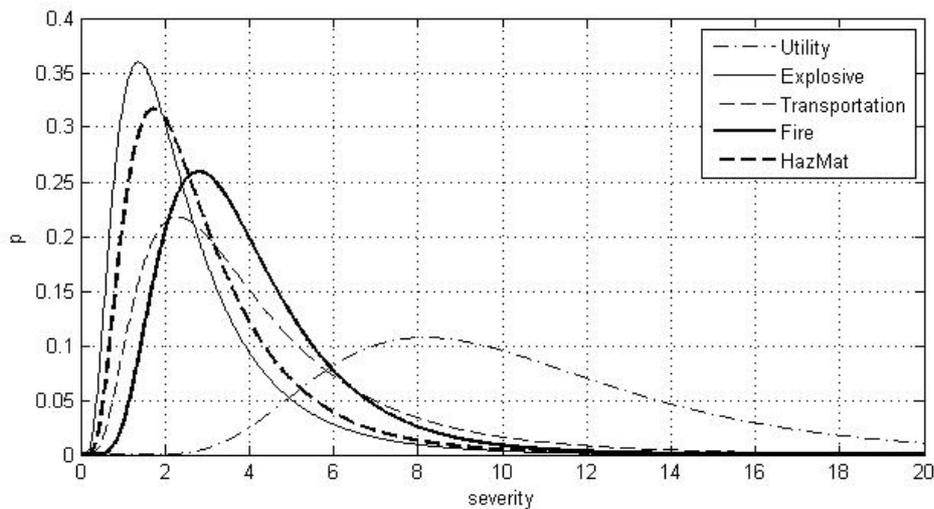

Figure 3. Severity distribution for incident types

Table 1: Transformation between incident types and demand

	Police	Fire Dept	EMS	Public Works	Utility
Utility	-	-	-	yes	yes
Explosive	yes	yes	yes	-	-
Transport	yes	-	yes	-	-
Fire	yes	yes	-	yes	-
HazMat	yes	yes	yes	-	-

2.10 The emergency response environment is modeled within a two dimensional square map, measuring 100 by 100 cells, and divided evenly into 16 jurisdictions (each 25 by 25 cells). At the beginning of each simulation run (time zero) there was no demand on the map. At each unit of time, an increment of demand was added (by means of stochastic sampling) and agents sought to respond to this demand. This setting implies that the simulation needed some *warm-up* period before the system reaches a "typical" stable equilibrium. For each condition (set of initial parameters), we performed 50 simulations and reported the mean and standard deviation of average response time. We tested all six communication patterns for every set of parameters. The parameters that we varied during the experiments include the following:

- Sight range of the agents (R) - the distance from which the agent could 'see' the demand. This parameter has a crucial meaning from an information perspective and can be interpreted as describing the amount of information available to the organization.
- Probability of establishing contact between agents (P) - when two (or more) agents meet at the demand site, they may establish a professional contact that would lead to exchanging information in the future.
- Discount over time in contacts between agents (T) expressed in simulation time units (STU). In practice, current social contacts may decay over time, while new contacts are established. This parameter defines the period after which professional contacts disappear.

2.11 Finally, we addressed a finite resource problem. Each agent is assigned a limited number of resource units. If the incident requires more resources than an agent has, it provides all its resources and then is re-positioned to its initial location and its resources are restored.

🌐 Findings

3.1 In the first set of experiments, we tested the influence of controlled variables on the response time of organizations by setting the variables to the following values: R = {2, 5}, P = {0.1, 1}, T = {100, 1000}. The primary criterion in effective response is to minimize the time required for emergency vehicles to arrive at the scene of the incident. The results presented in Figure 4 show that any form of communication significantly decreases response time, relative to the setting in which the organizations do not communicate at all (000). Even for the scenario where there is only informal communication among street level agents (00A) and a relatively small probability of establishing communication links between agents (P=0.1), the average response time of organizations was decreased by almost one third. From our earlier results (Comfort et al. 2004), we concluded that the behavior of our models is especially sensitive to the change in information available to the agents (agents' site range).
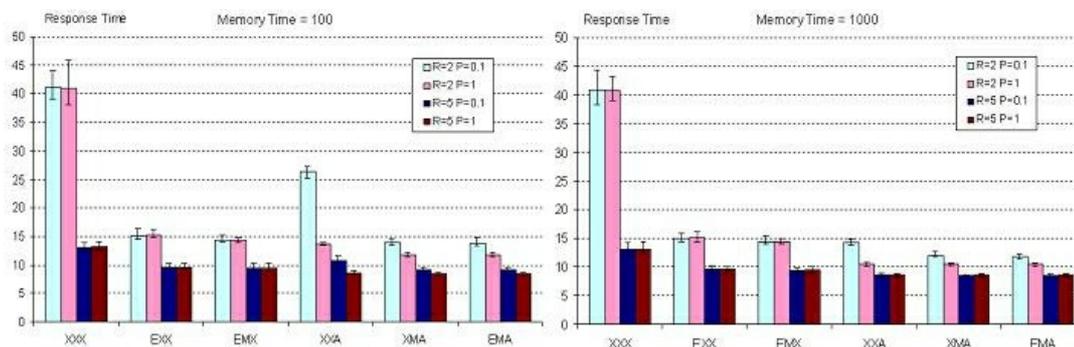

Figure 4. Response time by communication structure

3.2 The results discussed above confirm that the simulated system achieves a high level of efficiency when agents are allowed flexible communication. What kind of structural mechanisms makes the system more efficient? To answer this question, we examine the exchange of information among agents within the network (Miller and Moser 2003). We apply the methods of network analysis (Newman 2003; Wasserman and Faust 1994; Wellman 2001) to investigate how interactions among agents form a dynamic network.

3.3 At the initial stage of larger events, we can expect the disconnected networks among agents and organizations. The destruction to existing infrastructure and personnel resulting from the Great Sumatra-Andaman Earthquake of 26th December 2004 illustrated the severe limitations imposed upon organizational response capacity. Under such extreme conditions, the disaster response network was seriously dysfunctional. The critical mission of response organizations is to form an efficient information exchange network. In our framework, the early stage of simulation illustrates such a situation. However, understanding the mechanisms governing situations when a social network is severely altered by a large magnitude event would require separate study and more detailed observation than mentioned above.

3.4 Such an initial disconnected network evolves into a more connected network through interactions among agents. We observe that the interaction and communication among agents create an efficient network structure. Figure 5 shows the change in average degree of the network (e.g., average number of direct contacts by agents for each node). The average degree of the network increases gradually until around 250 STU and grows rapidly after that point, reaching stability at around 1000 STU. This finding implies that flexible communication among agents allows the network to be connected rapidly. For a detailed examination of flexible communication, we review the change in average distance (the average length of the shortest path for each pair of nodes). In the early stage of the simulation, the average distance is small because disconnected nodes are not included in the calculation of distance. But the average distance increases gradually and reaches its peak around 175 STU. At this threshold, the network formed a component in which all nodes are interconnected; the average distance became smaller and stabilized at the level of 2.4. Both the change of average degree and average distance show that the initial fragmented system self-organized into a well-connected network. [2]
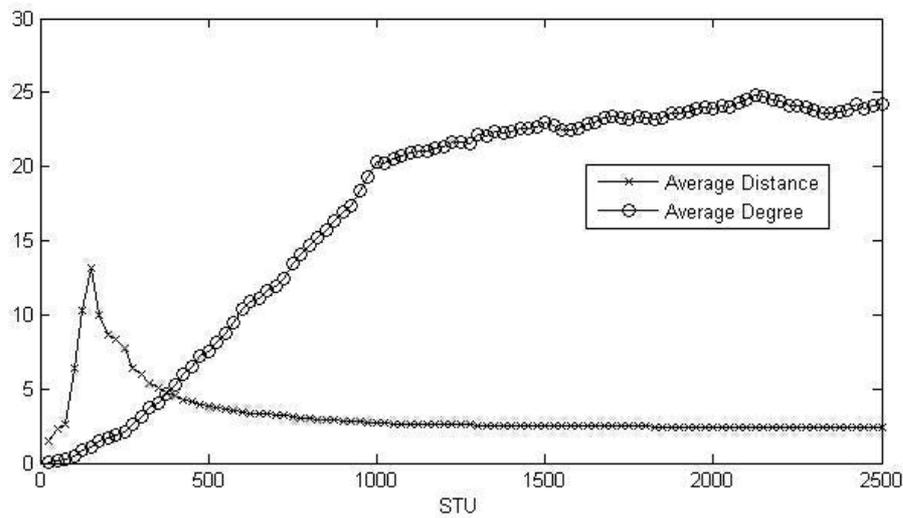
Figure 5. Change in average degree of communication by node within network

3.5   Within the information exchange network, the frequency of exchange among agents is not uniformly distributed, although we assume that the initial capacity of agents is. We measure how often agents exchange information. This distribution, shown in Figure 6 is similar to a lognormal distribution, but it has a heavier tail. This implies that some agents provide information more frequently than others. Unlike hierarchical organizations, the emergence of agents who play a central role in information exchange derives from a self-organizing process in response to immediate demands.
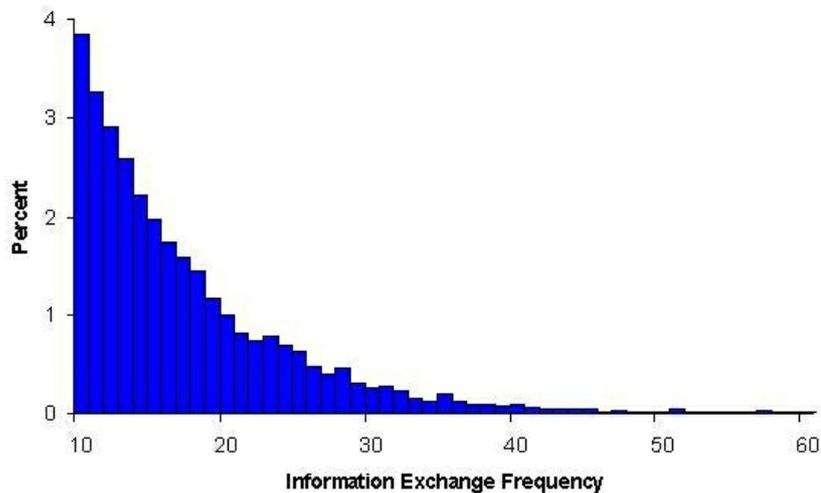

Figure 6. Distribution of information exchange frequency (R= 5)

3.6   An agent's information capacity, manipulated by changing the sight range in this simulation, also affects the frequency of information exchange. When information capacity becomes smaller (sight range is decreased from 5 neighboring cells to 2), the average frequency of information exchange decreases from 24 to 9. The role of the most active agent decreases from 243 to 90 information exchanges.

3.7   These network analyses of information exchange show that an initial fragmented network self-organizes into a well-connected network with short distance within a short time when we allow flexible interaction among agents. The level of information exchange among the agents is not the same, although they are initially homogeneous in their capacity and access to resources. Proponents of hierarchical organization argue that allowing flexible communication may cause coordination problems, but self-organizing network structure increases coordination as agents emerge and form important positions in the information exchange network. Heterogeneous agents not only deliver more information to other agents, but also increase the efficiency of the system. This design differs from other research that reports mixed findings for varied organizational designs under differing levels of stress (Carley and Lin 1995).

In future research, we will examine whether an informal structure formed by flexible information exchange supersedes formal organizational structure in actual disaster operations following an extreme event.

Conclusion

4.1 Using the agent-based simulation approach, we show that the efficiency of the response to recurring events is affected by the information search capacity of individual agents, the probability of networking, and the inter-organizational information exchange structure. When agents are permitted to search for information more broadly and when they are more likely to share this information with other agents, the response system can react to demands more quickly. One notable finding is that efficient response does not necessarily assume controlled communication among high level officers. Our simulation results suggest that information exchange among the lowest level agents is more efficient than that among managers and executives.

4.2 Given that many emergency response organizations prefer hierarchical communication as a means of control, permitting flexible communication among lower level agents may contribute to better cooperation not only within an organization but also between jurisdictions. Our simulation findings also suggest that the information capacity of individual agencies and legal constraints should be considered in designing the communication structure. Further, if the network is overloaded with information, the quality, not the quantity, of information processing will become crucial. Therefore, the contextual differences that organizations face should not be underestimated.

4.3 The power of flexible interaction among agents is also observed in the evolution of networks over time. Although the initial capacities of agents are not so different and there are no authoritative actors controlling interactions among agents, some agents actively engage in information exchange and connect more frequently with other agents. Such a self-organized process of network evolution leads to a well-connected network. Of course, if we consider costs and benefits for networking and the quality of information that agents have, we might expect a different network structure. Particularly, large scale crises have different demand functions and efficiency measures, and should be modeled accordingly. Despite this limitation, we find that flexible networking makes agents reach each other for collaborative action within a short distance.

4.4 Finally, agent-based simulation can be a useful tool for simulating various types of network structures. While traditional social network theory provides a useful analytical framework for analyzing given networks, it has limitations in dealing with dynamic change in networks. Agent-based simulation will be useful for generating models of diverse types of networks based on more realistic assumptions.

Notes

[1] Personal communication, Emergency Service Chief, September 2004.

[2] This finding is consistent with Albert L. Barabási's concept of the emergence of a 'giant component' in recurring interactions among pages in the World Wide Web (Newman, Barabási, and Watts 2006 , p. 170.)

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