Complex Systems in Crisis: Anticipation and Resilience in Dynamic Environments

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Confronted with increasing risk and uncertainty from disruptive change, public managers seek methods to strengthen the capacity of their interdependent organizations to anticipate risk and demonstrate resilience in response to threat. The problem intensifies for public organizations that interact with private and nonprofit organizations to protect a community at risk from natural or technological disasters. It reflects the constraints placed upon human decision processes in complex environments by limited cognitive capacity, and illustrates the persistent difficulty in achieving coordination among multiple organizations with different responsibilities in different locations in serving the public interest.

This article summarizes current research on the design and development of an interactive, intelligent, spatial information system (IISIS) for decision support in the mitigation of, and response to, risk from hazardous materials for a university community. Appropriate uses of the IISIS prototype are expected to increase both the technical and organizational capacity to manage timely, accurate information exchange within and among organizations, thus increasing coordination in action.

Introduction

Increasingly, public organizations confront conditions of 'permanent whitewater' that is, social, economic and political environments that are fraught with risk and rapid change. Such environments require a different mode of organization, information processing, and leadership skills from the traditional forms of management and control. The problem is how to increase the capacity of interdependent public organizations to anticipate risk and demonstrate resilience in response to threat.

This problem intensifies for public organizations that interact with private and nonprofit organizations to protect a community at risk from natural or technological disasters. Organizational performance repeatedly declines in environments of increasing complexity, and previous efforts to address this problem have considered it essentially insoluble.[1] Increases in organized complexity require significant increases in information flow, communication, and coordination in order to integrate multiple levels of operation and diverse requirements for decisions into a coherent program of action. Further, these different levels of operation each have different constituencies who need to understand the rationale and timing for co-ordinated performance in order to attain a common goal.

Yet, human decision makers have limited cognitive capacity. In rapidly changing environments, they are often unable to process the amount and range of information required to make timely, informed decisions essential for adequate coordination among the multiple components of the response system. The sequence of organizational decisions repeatedly falls out of synchronization with technical requirements for mobilization of action. Accordingly, organized performance in complex environments has been viewed as necessarily limited by human information processing capacity (La Porte, 1975).

Advances in information technology and telecommunications allow means to overcome the long-observed decrease in organizational performance in complex environments. Technical capacity to order, store, retrieve, analyze, and disseminate information to multiple users simultaneously creates the potential for innovative approaches to collective learning and self organization. These means extend information processing capacity beyond the limits of single individuals, and provide decision support to multiple managers addressing the same problem at different locations at the same time. Linking

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organizational capacity for mobilizing the resources of a community to appropriate uses of information technology creates a 'socio-technical system' in which technical capacity to exchange timely, accurate information among multiple participants increases organizational capacity to solve shared problems that require action at local, regional, national, and international levels.

This article addresses the problem of mitigation of risk and mobilization of response to disaster. This problem returns to the earlier discussion of risk initiated by Aaron Wildavsky (1988) in his seminal book, *Searching for Safety*. Writing in an earlier time and context, but noting both the prevalence of risk in social contexts and the ineffectiveness and cost of traditional efforts to control it, Wildavsky (1988) proposed creating a balance of 'anticipation' and 'resilience' as a strategy for reducing risk in uncertain conditions. To Wildavsky, anticipation meant a careful assessment of vulnerability in the community, with prudent action taken to limit obvious danger. Resilience meant a flexible response to actual danger, demonstrating an ability to 'bounce back' after a damaging event. While Wildavsky relied upon a combination of systematic actions to reduce known risk and the capacity to act quickly in the event of uncertain danger, such a strategy places an heavy burden upon human decision makers to calibrate their decisions on the basis of judgment bred from experience, with little recourse to external sources of decision support (Comfort, 1994b).

Current approaches to disaster mitigation seek to integrate the technical capacity of information technology with organizational design and communication processes among major actors to create a community-wide system for risk reduction and response. Such an approach echoes Wildavsky's earlier strategy of seeking to balance anticipation with resilience, but explores the additional potential of fostering self organization and organizational learning in a continuing process of community risk reduction and response. This article presents findings from a pilot project to design and test a prototype interactive, intelligent, spatial information system (IISIS) at the University of Pittsburgh to anticipate and respond to risk from hazardous materials for a community of 32,000. The prototype identifies possible ways to improve inter-organizational and inter-jurisdictional performance in risk reduction and response through the appropriate design and application of information technology.

Policy Problem: Coordination Within and Between Organizations in Disaster Environments

Disaster environments present an extraordinarily difficult context for inter-organizational and inter-jurisdictional coordination. When disaster threatens a community, it requires different responses from different organizations at different locations to set aside prior activities and focus time, effort, and attention on a common goal. To achieve a coordinated response, these actions must be taken simultaneously. Coordinated response is particularly difficult to achieve with threats such as hazardous materials in which the general vulnerability is known, but the specific time, location, and magnitude of the threatening event are uncertain.

Coordination under uncertain conditions requires an understanding of shared risk (Comfort, 1997; 1999). When risk is shared, actions taken by any one person may increase the risk, escalating the event into a wider disaster for all persons exposed, or reduce the risk, bringing the threat under control and limiting the consequences for the entire community. Informed action, guided by a shared goal of protection of life and property for the community, becomes a primary strategy for disaster reduction and response. But the critical difference lies in identifying the potential chain of assistance prior to mobilization for a given event, and building the information infrastructure to support mobilization, should the need occur.

We propose that the capacity of a community to take informed action can be significantly strengthened by appropriate uses of information technology (Comfort, 1993; Comfort et al., 1998; National Research Council, 1996). Returning to Wildavsky's insightful recognition of the need for both anticipation and resilience in managing risk effectively, we explore the potential of information technology to provide a more consistent and reliable means of decision support to practicing managers operating in uncertain conditions. While the actual decision to mobilize emergency operations remains the function and responsibility of human managers, appropriate uses of information technology may significantly improve the validity, timeliness, and accuracy of information available to them to manage such events. The result is likely to increase effectiveness in organizational performance in complex, dynamic environments.

Designing technology to support coordinated action in complex environments requires both technical and organizational planning. Such planning needs, first, to create an awareness of risk in order to define effective action within and among organizations in an actual event. In

Wildavsky's terms, this step can be identified as 'anticipation.' Second, effective planning needs to involve the first level of response, where initial steps taken to reduce risk for the community influence subsequent opportunities for action in a rapidly evolving disaster event. This step can be designated as 'resilience.' Both concepts operate in dynamic tension which, if managed appropriately, can produce an effective strategy for risk reduction and response. Each uses information in different ways, but both are directed toward action. A strategy of anticipation builds upon a careful assessment of the community to identify not only its vulnerabilities to risk, but also its likely points of strength and safety. A strategy of resilience identifies the capacity of a community to mobilize action in response to threat, once it has occurred. Both strategies need to be specified in terms of what organizational resources exist in a given community, what actions fall within the acceptable range of emergency response, and which organizations are responsible for what tasks within the critical time frame for response.[2]

The organizational capacity of a community includes public, private, and nonprofit organizations as well as households. In order to increase its capacity to reduce and respond to disaster effectively, the community needs to use a range of information technologies to create an information infrastructure that provides decision support to its participating members. An effective decision support system would facilitate coordinated action first, within the community prior to a threatening event, and second, between the community and external organizations in an evolving emergency response system. Such a decision support system would assist the missions of local, state, and federal emergency management agencies by supporting the mitigation and management of risk in a systemic framework.

Theoretical Framework: Self Organization in Complex Adaptive Systems

The theoretical concept of self organization underlies the design of a decision support system to support coordinated action in community response to disaster. Self organization is the spontaneous reallocation of energy and action to achieve a collective goal in a changing environment (Kauffman, 1993; Comfort, 1994a). This capacity to adapt to changes in the environment is observed in both social systems, when organizations adapt their performance to meet unexpected needs, and technical systems, where computers adjust the performance of systems operating in changing environments. For example, immediately following the 1987 Whittier Narrows Earthquake in the San Gabriel Valley of East Los Angeles, the traffic lights went out. Traffic backed up on city streets, and slowed to a standstill. In frustration, one driver pushed his car to the side of the road and began directing traffic at the next intersection, enabling other drivers of stalled cars to begin moving again. At other intersections across the city, drivers who had observed the first action, began to do the same. Without conscious direction, traffic began moving through the streets as 'citizen traffic cops' spontaneously assumed responsibility for coordinating the flow of traffic, a collective goal (Comfort, 1999). In computer science, the concept of self organization implies a similar process of searching for the most efficient flow of electricity around an unexpected set of obstacles, resuming the performance of an interrupted process with the best available route (National Research Council, 1996). This capacity for flexible adaptation to changing conditions is critical to maintaining effective performance in disaster environments in both social and technical systems.

Achieving self organization in both organizational and technical systems represents a substantial set of organizational and technical challenges. Four issues are central to the successful development and implementation of such a plan. They are:

Disaster as a mechanism of change

The perception of a policy problem directly influences the actions that are or are not taken in a social setting (Polsby, 1998). This general proposition is even more accentuated in the perception of risk or disaster (Douglas and Wildavsky, 1982). When disaster is perceived as the product of external forces, an 'act of God,' no action is likely to be taken, despite known risks and reasoned possibilities for change. But when disaster is perceived as the product of interacting and cumulative decisions between groups of people and their environment, coordinated action is possible if one identifies the critical points at which a response system evolves and provides timely, accurate information to decision-makers at those points. The evolution of the response system depends upon the timely flow of accurate information, and the level of awareness of decision makers at all levels of the system regarding the consequences of their specific actions for the performance of the whole system.

In this context, disaster is perceived as a mechanism of change. Potential risk need not be feared. Rather, recurring disaster can be viewed as a test of the existing policies of a community:

political, structural, social and economic. If basic community institutions and functions fail in a hazardous event, the ensuing disaster serves as evidence of the need for change. It creates the opportunity to redesign, revise or rebuild the human environment damaged by the event. Simply 'restoring the community to normalcy' recreates the likelihood of recurrence of similar disaster at a later time (National Research Council, 1996). Assessing the likely points of failure or vulnerability before an event occurs, and taking appropriate action to reduce the probability of failure represent a more productive strategy. This approach is the key premise underlying the Federal Emergency Management Agency's 'National Mitigation Strategy' (Krimm, 1997).

Reframing disaster as an evolving policy process

If disaster is perceived as a mechanism of change, it influences the choices – social, political, scientific, and economic – that are made by multiple sets of policy makers interacting in diverse ways. Actions taken during a disaster become defining elements for the (temporary) resolution of that disaster, but also likely steps toward the creation of the next disaster. A major function of disaster management is the accurate assessment of not only the specific causes of a particular incident e.g., an unanticipated release of hazardous materials, but also the interdependent functions and structures of the community that are affected by that release. This assessment provides a means of monitoring the impact of hazardous materials upon the community, but its validity depends upon the degree of access to, and quality of information about, the community available to policy makers before the release occurs. It depends as well on timeliness in communicating risk to community managers who have the legal responsibility to protect people and property. The actual choices they make either reduce or exacerbate the evolving crisis, sometimes in both directions simultaneously.

A decision support system that facilitates self organization recognizes the dynamic nature of disaster and focuses on decision points that enhance or reduce the likelihood of its occurrence. Mapping this continuously evolving pattern of interaction is an important, but difficult, function of disaster management. This interaction is interdisciplinary, inter-organizational, and inter-jurisdictional. Only recently has the scientific and technical capacity including satellite communications, remote sensing, and GIS analysis existed to support this assessment on an ongoing basis. Scientific and technical capacity generate further possibilities for interaction among community participants that exceed the possibility for organizational control. The system either becomes self organizing and establishes a more appropriate order for the changed environment, or it disintegrates into chaos and disaster.

Local conditions as governing elements in evolving disaster response systems

When the complexity of interacting scientific, social, political, and economic conditions exceeds the existing capacity for organizational control, decisions taken by local actors govern the direction of the evolving process (Prigogine and Stengers, 1984; S. Kauffman, 1993; Gell-Mann, 1994; Comfort, 1994a; Comfort, 1997). Since disaster means loss of control, investment in improving capacity for organizational response at the local level is likely to generate the greatest benefit to the community. Failure to improve capacity in the first response is likely to undercut any other measures undertaken for disaster reduction. An interactive, intelligent, spatial information system designed to support coordination among the participating actors and administrative organizations of the community would greatly reduce the risk of disaster and enhance its capacity for response to extreme events.

Coordination in self-organizing systems

Coordination among actors such as individuals, organizations and jurisdictions has long been sought in research in organizational theory, without much success (Caiden and Wildavsky, 1974). The requirements for coordination – monitoring performance of a complex system and sharing that information to support timely action by many participants seeking a common goal – have been difficult to achieve in dynamic environments through standard administrative practices.

Information technology now provides a means of decision support that enables coordination among multiple organizations and jurisdictions. While coordination of action among participants is frequently recommended as a solution to complex, interdependent problems such as shared risk, planners and policy makers have found it difficult to implement in practice.[3] Administrative theorists have not been able to define coordination in ways that do not imply coercion (Caiden and Wildavsky 1974; 277–279), or to devise means of facilitating coordination without compromising the shared goal (Wilson 1989; 268–274). Theorists critical of coordination have viewed it primarily as a problem of control. They have defined it as a set of organizational procedures that requires multiple participants with different levels of training, understanding and responsibility to follow a common set of rules, often externally imposed, to achieve a complex goal.

Coordination in disaster operations is largely achieved by different means. While emergency response agencies often share similar training and operate within a similar framework for response, e.g. international fire training or the Incident Command System, coordination depends substantially upon processes of information search, exchange and feedback that produce both intra- and inter-organizational learning. The detail, accuracy, and timeliness of the information exchange among them shapes the process, as the organizations strive, individually and collectively, to achieve a common goal. Through learning processes, coordination becomes mutual adaptation, or self organization. The goal of a community emergency planning process is to enable the community to become self organizing in the reduction of risk and response to disaster.

Methodology

The design of a self organizing system is based upon the concept of an N-K system developed by Stuart Kauffman (1993) to assess change in dynamic environments. In his assessment, Kauffman identifies the number of organizations (N) that are interacting to achieve a collective goal (P), and the number of interactions (K) among them. This design has been extended in studies of response systems following earthquake disasters to include the number and type of transactions performed by organizations directed toward this common goal (T), the duration of their involvement in the response system (D), and the source of funding (S) for their activities (Comfort, 1999). These measures serve as indicators of an evolving response system that changes over time. They are summarized as follows:

P = purpose (goal) of the evolving system
N = number of organizations participating in the system
K = number of interactions among organizations participating in the system
T = type of transactions performed by participating organizations to achieve system goal
D = duration of activities performed by system participants
S = source of funding for participating organizations

These measures guide the detailed task of mapping the decision processes for an interorganizational response system in practice. The next section summarizes current research that is developing a prototype decision-support system to facilitate self organization in an actual community exposed to risk.

Interactive, Intelligent, Spatial Information System (IISIS)

A prototype interactive, intelligent, spatial information system (IISIS) is under development at the University of Pittsburgh to support inter-organizational coordination in hazardous materials management (Comfort et al., 1998). While the general design of IISIS supports a self organizing response system, the actual system needs to be fitted to the conditions, context, and actors for the specific community in which it is implemented. This requirement has both advantages and disadvantages. The advantage is that an IISIS, carefully designed and fully implemented, creates a community-wide knowledge base that can be used to provide inter-organizational decision support for many types of policy problems. The disadvantage is that maintaining the knowledge base in order to provide current, valid information is a continuing task that requires commitment, cooperation and coordinated action among the members of the community who use it for decision support. The two conditions are reciprocal. A community-wide knowledge base, when it is current and valid, demonstrates its value in addressing complex policy problems and likely increases commitment by members of the community to maintain it. Should maintenance falter and the data become outdated or invalid, its value to decision processes decreases, and consequently, its ability to support coordinated action also decreases. The process is one of continual monitoring, learning and adaptation for both organizational and technical systems.

An IISIS links two types of information processing systems: 1) the technical system of computers; and 2) the human cognitive system of decision makers and their respective organizations (Weick, 1990). Both systems are amplified by networks of communication among multiple computers for the technical system and many decision makers for the organizational system. The load, rate, and complexity of information that is transmitted within and among organizations in dynamic disaster operations is massive. Without technical support, the information processing demands overwhelm the cognitive capacity of individual managers and organizations to absorb, process, and use the flood of incoming information as a basis for timely, informed action. Using distributed knowledge bases and a network of computers operating in parallel, the technical computing system is designed to support the human organizational system in its conduct of distributed, parallel operations in response to a given hazard. A distributed system requires an effective means of electronic transmission that is reliable and readily available. The Internet performs this function, but given its increasingly heavy load, it becomes less reliable for emergency communication. A major question to be investigated in any community development process is to determine the most reliable and robust mechanism for the electronic transmission of data under emergency conditions.

Technical advances allow the integration of visual data with intelligent reasoning and interactive communication, using a blackboard model that provides virtual real-time information to support decision making for personnel operating in the dynamic environment of disaster operations. Logical inference by the computer will incorporate probability estimates to capture the anticipatory logic characteristic of disaster managers who seek to bring order to a dynamic, uncertain set of conditions. The prototype IISIS will function as a distributed, parallel processing information system that is expected to increase the efficiency of decision support for practicing managers. A working demonstration of the IISIS design may be viewed on the Internet.[4]

The IISIS Design in Practice

Fitting the IISIS concept to an actual community requires the specification of decision points, databases and linkages both technical and organizational horizontally among multiple organizations within a single jurisdiction and vertically across multiple jurisdictions within a given response system. The technical capacity for rapid performance of complex information functions supports the organizational capacity to anticipate risk to the community before it occurs, and to support actions by multiple parties operating at different levels of responsibility to reduce the likelihood of threat in an informed, systematic manner.

For example, the University's capacity to identify rapidly and accurately the number, types, quantities and locations of hazardous materials stored in its laboratories, storerooms or physical plant operations rooms can support a program of responsible management of those materials and limit exposure to University students, faculty and staff. This same information infrastructure, constructed horizontally within and among the University's administrative and operations units, can, if connected vertically to city, county, state and if necessary federal emergency response organizations, facilitate resilience in response to an actual release. If the University's Environmental Health and Safety Department identifies accurately not only the type, quantity and location of the release, but also the number of people and location of critical infrastructure at risk and communicates this information to the City of Pittsburgh's Hazardous Materials Team, the response to the release can be mobilized quickly and effectively with minimum damage. The University, under threat, relies upon the resilience of the larger emergency management system to access City resources, reduce the risk of escalation, and bring the incident quickly under control. It is the combination of horizontal with vertical organization that provides the University campus with flexible, but professional, management of risk.

While the specification of decision points, databases and linkages has not yet been carried out in a detailed way for an actual emergency event, evidence of both horizontal and vertical decision processes from the University of Pittsburgh are used to illustrate the potential for increasing coordination in a dynamic response system and to serve as a model for the design of a sociotechnical system for disaster mitigation and response in communities exposed to risk. The design incorporates Wildavsky's concepts of anticipation and resilience as the basic strategy for risk reduction. The challenge is to determine the appropriate balance between the two, given the degree of risk and resources available in any given community.

The IISIS design includes four jurisdictional levels, following the basic format of the Incident Command System (ICS) widely used in emergency response and fitting the requirements of the university to the city, county, state, and federal levels. The Federal Response Plan, implemented for the twenty-eight federal agencies that have emergency responsibilities and used by the Federal Emergency Management Agency (FEMA) as its governing format for emergency response operations, serves as a guide to the system-wide design.

Within each of the four vertical levels – municipal, county, state and federal – are organizations with specific responsibilities for emergency response. Previous planning efforts had specified guidelines only for public organizations with legal responsibilities for emergency response (Comfort, 1985; California OES, 1992; FEMA, 1992). Widening this process to include relevant nonprofit and private agencies with resources, knowledge and capacity for response at each of the four jurisdictional levels increases both the complexity and the potential effectiveness of the model. This model presents a preliminary design for a sociotechnical system, using the example of the University of Pittsburgh, a nonprofit organization that functions as its own jurisdiction.[5]

Developmental Process

The first phase of a developmental process for a prototype information infrastructure to support inter-organizational decision making and coordination for reduction and response to risk from hazardous materials at the University of Pittsburgh continued over a period of seven months, October 15, 1998–April 15, 1999. This developmental process sought to produce three outcomes:

1. A coherent, multi-disciplinary group of faculty, administrators, staff, and students, each with different responsibilities in disaster reduction and response, different capacities for action, different resources available for their use, and different requirements for information, that accept the common goal of the disaster mitigation and response for the campus community;
2. A detailed method for collecting, organizing, processing and transmitting relevant data from each campus unit, as well as the interdependencies among the units, through a distributed information system that will provide easy access and near real-time information on a rapidly evolving situation to relevant participants in a campus-wide response system;
3. The demonstration of a working prototype IISIS to practicing managers for their review in the development of a self organizing system of disaster reduction and response.

The prototype IISIS that emerged from this development demonstrates the capacity of the University community to engage in a self organizing process of reduction and response to hazardous materials and other risks on campus. This demonstration reflects the work done by the participants in the process, and represents their commitment to the campus-wide goal of risk reduction and response. The findings from this project serve the critical function of documenting the design, functions, and implementation of a sociotechnical prototype for risk reduction and response. This project represents the first effort to translate a theoretical model of a self organizing, sociotechnical system into practice for an actual community exposed to risk from hazardous materials and other threats.

A major function of this developmental process has been to identify both the resources and the vulnerabilities of the University community that could escalate or reduce risk from hazardous materials. Some of this work had been done through initiatives in emergency planning already underway (Environmental Health and Safety Response Plan, 1997). Some of the work has yet to be defined. No integrated knowledge base at the level of detail for individual buildings, departments, and rooms that is scalable to a campus-wide profile for effective disaster response existed prior to the project. The task of building a current, valid knowledge base to support inter-organizational decision making for reduction and response to disaster for the University, or any community, is substantial. This developmental process has begun the task, but there is still much work to be done to support informed, inter-organizational decision making among administrative units responsible for the protection of life and property of this community of 32,000 people.

The tasks involved in the developmental process are both organizational and technical. While these are substantively different sets of tasks, they have reciprocal effects on the performance of the campus response system. Each set of tasks was discussed separately to make explicit the steps necessary to achieve effective performance within their functions, but information was exchanged between the organizational and technical teams as they explored the constraints and possibilities that each brings to the design of a functioning sociotechnical system. The result is a more informed, broader group of policy makers who understand the limits and possibilities of both technical and organizational components of the University system, and who will be able to mobilize the strength of one component to offset the vulnerability in another. This is the benefit of a self organizing system in practice.

Some of the initial analysis of actors, tasks and responsibilities for action in emergency response was included in the University's Emergency Response Plan, prepared in 1991. The project's planning process has built on this work, moving to a more detailed and specific analysis of the information flow within and among University administrative units. This analysis has identified points at which the timely exchange of valid information among participating actors enables the system to reallocate its attention and resources in order to absorb changes in its operating environment and continue to function with reasonable effectiveness. It also identified points at which the operations of the system may be overwhelmed and require external assistance or a declaration of a state of emergency. In effect, the developmental process for the prototype has explored the flexibility and limits of the campus organizational system to adapt to altered circumstances. Achieving the most efficient and effective flow of information through the University response system has both organizational and technical requirements. Planning for these two sets of functions must proceed with close coordination among the organizational and technical personnel responsible for the University system.

While the overall goal of the IISIS Project is the design, implementation, and evaluation of a decision support system to support coordinated action to reduce risk, this report summarizes only the developmental phase as it has been carried out in the field environment of the University of Pittsburgh. It presents a preliminary map of the decision processes for the University resulting from this process, but omits the detailed information for campus facilities that is protected for confidential reasons. This map of decision processes would guide the dynamic search for, and exchange of, information among University administrative units that represents a strategy of anticipation and resilience in practice. Carried out in practice, this process becomes a vehicle to facilitate the mutual coordination of actions among participating units in dynamic environments.

Data Collection

Data collection for this developmental process sought to identify the basic characteristics of a response system evolving over time for a community exposed to risk from hazardous materials, as well as the threshold points of change in the evolution of a response system. Data collected at the administrative unit level is organized for the knowledge base according to known standards, e.g. the National Spatial Data Infrastructure (NSDI) standards. Adhering to professional standards in the development of the knowledge base will facilitate common interpretation and shared meanings under the urgent pressure of an actual disaster. Applying the model of an N-K system to the University, we sought to identify the major components of the University's response system. The purpose protection of life, property and continuity of operations, or P, is accepted by all administrative units. All administrative units equally, as components of the University, a nonprofit organization, have the same source of funding, S.

Four types of data have been collected in the development of the IISIS prototype. These types include data regarding the existing conditions of University operations, as well as the organizational, technical, and operational characteristics of those functions. Data have been collected using several methods. First, data regarding the current state of the University's operations were gathered to provide an initial profile of its geographic location, academic mission, size, structure and population from a review of documentary materials and direct observation. Second, eight administrative units were identified as having primary and supporting roles in risk assessment and response for the University community. These units include: 1) Facilities Management; 2) Campus Police; 3) Environmental Health and Safety; 4) Emergency Medicine; 5) Telecommunications; 6) Registrar's Office; 7) Human Resources; and 8) Computing and Information Systems. Over the course of the planning process, the latter was reorganized into two distinct units, Computing Services and System Development, and Network Services. This set of units represent the N, or number of major actors, for the University response system.

With assistance from the staff of Computing and Information Systems, key types of information essential for response to a campus emergency were identified in their respective databases. Permissions were sought to access those databases, with proper authorization, for specific purposes of emergency management. The requisite permissions were granted by seven of the eight administrative units. Campus Police has a separate, proprietary database that can only be accessed through its vendor. The department, further, has legal requirements for confidentiality of information stored in its database.

With clear understanding that the data would be used only for risk assessment and emergency response, database links were created among the specified databases that support operational decisions by emergency response personnel. These databases included data on faculty, staff, and student personnel, class registration, pedestrian traffic on campus, assets, equipment, and types and quantities of hazardous materials stored on campus. The database links created a distributed system among the participating administrative units of the University. These database links represent the technical interactions, or K_t, for the University response system.

Third, technical data were gathered to provide accurate information on the technical infrastructure of the University. These data included a digital map of the campus with its buildings, floor plans for selected buildings on campus, detailed plans for the distribution networks of the lifeline systems: water, gas, electricity, sewage, telecommunications, and locations of the major points of intersection among the lifeline systems. These data provide the detailed information to support the rapid identification of transactions, or T, that would be carried out by the respective units of the University in response to the threat.

Fourth, patterns of information search, strategies for damage assessment, procedures and means of transmitting information in response to risk were identified through interviews with managers of each of the eight administrative units responsible for emergency action. These patterns, identified separately for each administrative unit, serve as the basis for identifying the threshold points of change and limits of a self organizing system for disaster reduction and response. These patterns also represent the organizational interactions, or K_o, for the University response system.

These four measures, N, K_t, K_o, and T, constitute a preliminary response system for planning purposes for the University of Pittsburgh. The remaining measure, D, for duration, is clocked in real time in disaster operations. It operates in conjunction with the knowledge base of detailed information about the University's plant and administrative operations. Together, the set of measures represents the pattern of horizontal interactions among administrative units operating within the University's jurisdiction.

Although the University is a legal jurisdiction responsible for life and property within its boundaries, it is dependent upon the City of Pittsburgh for critical fire and medical services. Since the University is located within the jurisdiction of the City of Pittsburgh, two of its primary emergency response functions, by law, report directly to City of Pittsburgh Emergency Services. Any incident that involves fire is reported immediately to the City of Pittsburgh's Fire Department. Similarly, any incident requiring emergency medical services is reported immediately to the City of Pittsburgh's Medic Command, which is located on the University campus but operated as a city-wide service. This relationship requires the University to coordinate its emergency response services closely with the City of Pittsburgh. This means establishing the vertical links for information search and exchange with the City as the next level of jurisdiction.

The IISIS knowledge base will be used to support coordinated action among the professional participants in an evolving response system at the University of Pittsburgh and, in event of escalation of danger, between the University and City emergency services. In later development, IISIS will have a public browser that may be accessed by the wider community and the nation.

In its fully developed form, IISIS will operate as a distributed system on at least two levels: professional and public. In its professional form, the prototype IISIS will use a custom-designed browser that is accessible only to authorized professional managers for use in community-related decision processes. This professional IISIS allows managers to order, store, recall, and exchange information relevant to seismic or other hazards in three different ways: 1) within organizations; 2) across organizations within jurisdictions; and 3) within a network of organizations that crosses jurisdictions. This capacity enables practicing managers working in positions of varied responsibility within the community's emergency management system to build quickly a shared information base in reference to a specific threat. This shared information base allows them to coordinate their actions more efficiently, thereby reducing the threat to the community and/or restoring threatened operations more quickly and effectively. In its public form, the prototype IISIS will allow community residents access to timely, valid information regarding the risk via any standard Internet browser, enabling them to mobilize their own actions more appropriately. The public browser will be read-only regarding the current status of the community, as the information will be posted directly from the Coordinator's status board. Community residents, however, may send information to the Coordinator regarding their condition or observations. This information will be verified and, if valid, incorporated into the dynamic knowledge base for the IISIS.

The set of expert interviews characterized the first level of information search, transfer and organizational learning in response to a threatening event for each administrative unit. Based upon these interviews, we have developed a map of potential information flow among the administrative units under emergency conditions. In one interesting finding, three managers described their risk assessment practices in similar terms. Each reported independently that he formed a mental model of 'good performance' in his area of operations. He judged the degree of risk or danger to operations in a given situation by the degree of discrepancy he observed between the actual situation and his previously developed mental picture. Each built his model of good performance on previous experience with the building, equipment, machines, or staff involved in operations. This finding confirms a theoretical model of problem solving (Weick, 1993) that shows human beings are able to assess risk or danger more quickly through visual and aural clues than by following procedural rules.

In continuing development, a second level of detail would be added for each of the administrative units. This effort would create a departmental knowledge base that would guide the daily operations of each administrative unit, so the data would be current and maintained by unit staff. In an emergency, with proper authorizations, these departmental knowledge bases would be accessed to provide timely, valid information to the campus emergency co-ordinator through the IISIS distributed network. Specifically, eight administrators with responsibilities for different types of operations defined under the University plan were interviewed to elicit their judgment regarding the critical points of decision within their units that activated emergency response, as well as the points of coordination among the different University units in response to threat. These judgments indicate the threshold points of change in the evolution of a response system, as well as the points at which the system would lose coherence.

The intelligent reasoning component for the IISIS is in its initial stages of development. The current design of IISIS uses a blackboard system that allows opportunistic problem solving (Nii, 1986) based upon the specified responsibilities and resources of participating members of the response system. That is, incoming information regarding an actual problem is posted on an electronic blackboard that is accessible to all of the authorized administrative units of the university in their respective offices or stations. As administrators from each unit read the message, they contribute information from their knowledge and experience for the solution of the problem. The evolving knowledge base serves as the focal point for coordinating action among the administrative units, as each unit adjusts its response to the incident, informed by knowledge of the other units' actions, resources and capacity.

This model fits the theoretical design for a self organizing system. Standard operating procedures specified in the University's Emergency Plan can be adapted as parameters for emergency operations by individual units. During this period of development, we are also exploring two other forms of intelligent reasoning as complementary to the blackboard system. One is an intelligent reasoner, GeNIe, developed by Marek Druzdzel in the School of Information Science, University of Pittsburgh. This program identifies the goal of a system, the component variables of the system, and the relationships among the variables. The reasoner then calculates the probability of risk or action for the whole set of variables, or the system. This program is still in its developmental stage, but the logic is clearly traceable across sets of conditions, interactions, and jurisdictions. The third reasoner that we have explored is NetWeaver, developed by Michael Saunders and Bruce Miller of Penn State University. This reasoner uses fuzzy logic to approximate the often ill-defined, dynamic conditions of emergency environments. These technical issues are currently under development.

Data analysis

Data from the expert interviews served as the basis for mapping the flow of information through the university administrative units in event of a hazardous threat. This map identifies points where coordination with other units is essential and where gaps in the current communication patterns may exist in University response procedures. Next, we constructed a system diagram to show the current knowledge base used by each unit for decision support, with its existing software for access, storage and format of data, and noted points of compatibility or difference among them. From the interview data and the system diagram, we identified a preliminary set of information requirements that is essential for coordinated action in response to disaster. This set of information requirements has been reviewed, revised and validated by the practicing managers. The result is a map of the decision process among interacting administrative units, showing the exchange of information essential to support timely, coordinated response by the University system. This analysis follows the organizational audit and analysis techniques developed by Kenneth Mackenzie (1984) for dynamic organizations. This set of methods produces a task/process matrix, or detailed specification of who performs what tasks using what resources within what time frame for the organization. It reveals not only the points of communication and reinforcement in organizational action, but also the gaps in communication and the likely points of vulnerability over time. This preliminary matrix of the existing response system for the University community is presented in Table 1.

Preliminary Map of Decision Processes in Response System

The map of the decision processes, even at this preliminary stage, reveals some interesting aspects regarding the University's response system. First, there is a clear distinction in terms of information search between the units with first response functions Facilities Management, Public Safety, Environmental Health and Safety, and Emergency Medicine and those with secondary response functions Telecommunications, Registrar's Office, Human Resources, and Network Services.[6] Within minutes of the first report of an incident, these units respond to the call with action. The secondary units confirm the report before they take action. Summaries of the information flow charts for the eight administrative units are included in the Appendix.

Second, the departments with first response functions appear to respond independently of one another to perform functions for which they have specific responsibility. While this strategy may be effective for unit level incidents, it does not serve the need to inform all units simultaneously should the threat escalate quickly to a campus-wide threat. Third, there is a

Table 1: Preliminary Map of the Decision Processes: University Response System

Tasks	Facilities Management (8:00–5:00)	Facilities Management All other times	Public Safety	Environmntl Hlth&Safety	Emergency Med.Svcs	Telecomm.	Registrar's Office	Human Resources	Network Services
Initial Response: T0–T15 minutes									
Information Search: Unknown Threat									
Initial call	IC	NDO	IC	IC	IC				
Log information	LI		LI						
Dispatch officer to scene	DSP	DTA	DSP	DSP	DSP				
Information Search: Technical Malfunction									
Report of Service Disruption	IC	NDO				SVD			SVD
Search for cause, location of disruption	LI					ISD			ISD
Dispatch technician to restore services	DSP	DTA				DSP			
Search for information on status of campus						ISC			ISC
Information Exchange									
Officer reports findings to manager	RPT		RPT	RPT	RPT				
Manager notifies other relevant units	IFX^1	IFX^1	IFX^1	IFX^1	IFX^1				IFX
Actions Taken: On Campus (Horizontal)									
Manager assesses situation	DTA		DTA	DTA	DTA	DTA			DTA
Respond to emergency call			RSP						
Establish command post				ECP					
Clear area of injured people				CLA					
Treat patients					TRP				
Clean up minor spill				CLS					
Restore operations, if possible	RSO	RSO	CAA			RSO			RSO
Request internal assistance, if needed	RIA	RIA		RIA					
Close incident response, if needs are met			CIR	CIR	CIR				
Request external assistance, if necessary	RXA	RXA		RXA	RXA	RXA			RXA

Legend:

IC = Initial call	DTA = Duty Officer's/Director's assessment of risk	RPT = Report findings
LI = Log information	IFX^1 = Information exchange (CAMPUS)	ECP = Establish command post
DSP = Dispatches engineer/technician/ sets tasks	IFX^2 = Information exchange (City)	CAA = Control access to area
RSP = Responds to call/request for information	RXA = Requests external assistance (next level authority)	CRS^2 = Coordination shifts from City to County
NDO = Notify duty officer (Facilities Management)	CRS^1 = Coordination shifts from Campus to City	CLA = Clear area of injured people

Tasks	Facilities Management (8:00–5:00)	Facilities Management All other times	Public Safety	Environmntl Hlth&Safety	Emergency Med.Svcs	Telecomm.	Registrar's Office	Human Resources	Network Services
Vertical Shift: Response									
Coordination shifts to City of Pittsburgh			IFX^2, CRS^1	IFX^2, CRS^1					
Media Response Team arrives			MRT	MRT					
Coordination shifts to Allegheny County			CRS^2	CRS^2					
Recovery									
Move to Recovery Phase				RCV	RCV				
Provide information services on campus						INS			
Manage clean up operations	RCV		RCV	RCV					
Secondary Response: Support Functions									
Information Search									
Receive report of incident						IR	IR	IR	IR
Confirm incident report w/ Public Safety, Admin.						CFR	CFR	CFR	CFR
Information Exchange									
Use runners to exchange information, if technical means are nonoperational						IFX^1			
Actions Taken									
Manager assesses state of unit's operations								DTA	
Manager determines actions for unit								DSP	
Manager assesses state of campus operations						ISC			
Form unit team for response							FRT		FRT
Respond to requests for information							RSP	RSP	RSP
Request internal assistance, if needed							RIA		
Seek alternate routing for communication						SAR			
Verify information re: University records, rosters							VRI	VRI	
Organizational Learning									
After Action Review of Unit's Operations							AAR	AAR	AAR

Legend:

CLS = Take action to clean up minor spill
MRT = Media Response Team responds to media, if major risk
RCV = Recovery, clean-up process when release under control
TP = Treat patients
CIR = Close incident response

SVD = Report of service disruption
ISD = Information search for source of disruption
ISC = Information search on status of campus
SAR = Seek alternate routing for communications
INS = Telecom.provides information services to campus
VRI = Verify information

CFR = Confirm report with Public Safety
FRT = Form response team to meet requests
RIA = Request internal assistance from campus
HRS = if Human Resources secure, serve campus
AAR = After action review of performance
RSO = Restore operations

significant distinction, particularly in Facilities Management, between response actions taken during normal working hours, M-F, 8:00–5:00, and all other times. Finally, the decision processes reported vary significantly from the 1991 University Emergency Plan. The 1991 emergency plan essentially relies on 911, or an emergency call to the City of Pittsburgh for any type of emergency other than a minor technical malfunction or spill. In fact, the administrative units of Facilities Management and Environmental Health and Safety have developed substantial technical and organizational capacity to respond to threats and to restore operations with campus resources. The 1991 Emergency Plan is currently undergoing revision, a necessary change as it no longer reflects the actual capacity for mitigation and response at the University. The University likely has a greater capacity for system-wide response than is reflected in its current plans and practice.

More work, however, needs to be done to achieve an effective balance of anticipation and resilience for the University community. This exercise revealed the need to update existing datafiles, to review existing patterns of communication, and to engage in a broader pattern of organizational information exchange and learning in order to attain an appropriate level of risk mitigation and response. The University has been extraordinarily lucky in that no major threat has occurred on campus for at least twenty years, but a sociotechnical approach is now available to enable the community to take a more reasoned, productive, and cost-effective approach to risk mitigation and response. It will require, however, a sustained program of investment, training of personnel, and monitoring of the 'state of the campus community' to maintain a continuing record of operations without major disruption.

Construction of a Community Knowledge Base

An important function of the IISIS prototype is to begin building the knowledge base for a University-wide decision support system, integrating three technologies: interactive communication, GIS, and intelligent reasoning. On campus, interactive communication is conducted through the University intranet, using the Oracle Web server. Security is established by setting clear criteria for authorized use, and extending access only to those professionals with responsibility for decisions during emergency events. If coordination should escalate to the city jurisdictional level, the same security procedures would be followed. Escalation of an event to city jurisdiction would require establishing agreements between the city and the university for city emergency response units to have access to the university knowledge base under emergency conditions. Such agreements, specified in advance with proper authorizations granted and constraints accepted by the participants, contribute significantly to a strategy of anticipation and resilience.

We are creating an initial geofile for the campus, which includes detailed plans of selected buildings and lifeline systems, according to National Spatial Data Infrastructure (NSDI) standards. These spatial data files will serve as a basis for a University GIS. We are currently developing examples for the intelligent reasoning component, using a blackboard system, Genie[7] and NetWeavers,[8] that incorporate the parameters for decision specified by the respective administrative units, building on the University knowledge base. An important function of the IISIS Project is to design and monitor the integration of these three components for robust performance under disrupted operating conditions. This work is being done, in conjunction with the faculty and industry experts in computation and communication techniques.[9]

Further development will require additional steps for the actual implementation of the IISIS prototype on the University campus or elsewhere. The project will utilize the disciplinary resources of the University in areas related to risk to continue building a knowledge base for interorganizational decision support GIS, emergency medicine, information science, public policy and organizational design. It will also identify areas of communication and coordination that need to be developed in order to reduce risk from hazardous events and to respond quickly when they do occur. Finally, increased efficiency will accrue from increased coordination among administrative units and members of the University community, facilitated by an interactive, intelligent, spatial information system.

Conclusions

In summary, four principal conclusions can be drawn from this research. They are:

1. Decision support systems, carefully designed and implemented, can assist public, private and nonprofit managers in reducing the vulnerability of their communities to hazards;
2. Given the complexity of disaster environments, such systems necessarily involve both technical and organizational components, operating in patterns of mutual

support to facilitate information flow within and among organizations participating in mitigation and response operations;
3. Maintaining an effective decision support system for the reduction of risk to a community requires a sustained program of mitigation, backed by investment in professional training and public education, for the community;
4. With effective sociotechnical decision support, coordination within and among organizations to reduce vulnerability to hazards can be increased.

Notes

1. This argument was documented in an earlier book chapter, 'Designing Resilient Communities: Self Organizing Processes in Disaster Management' published in Fukashi Horie and Masaru Nishio, eds. 1997, *Future Challenges of Local Autonomy in Japan, Korea, and the United States: Shared Responsibilities between National and Sub-national Governments*, Tokyo, Japan: Simul International, Inc.: 314–353.
2. The time frame for response differs according to conditions. Critical response in medical care varies from four minutes under life-threatening conditions to four days in exposure to threat. While emergency managers may differ on the precise time at which manageable threat turns to unsolvable danger, all would agree that shortening the time of exposure to danger lengthens the likelihood of life safety.
3. We are indebted to Emery Roe, University of California, Berkeley, for this observation on the role of coordination in administrative practice.
4. http://quake.ucsur.pitt.edu:5555/
5. This response system has been documented in an earlier paper, 'Self Organization in Disaster Mitigation and Management: Increasing Community Capacity for Response,' by L. Comfort, Y. Sungu, M. Huber, J. Piatek, M. Dunn, and D. Johnson, and presented at the 1999 Conference of The International Emergency Management Society, Delft Technical University, Delft, The Netherlands, June 7–9, 1999. This account relies heavily upon that paper.
6. After the reorganization of Computing and Information Services, the information flow patterns changed to some extent between the two new divisions. The matrix reports the pattern of response for Network Services, since the CIS expert interviewed during the data collection process continued as director of this division.
7. GeNIe is being developed by Marek Druzdzel and his graduate students in the Intelligent Reasoning Laboratory, School of Information Sciences, University of Pittsburgh. We are pleased to incorporate their work into the IISIS prototype as an integral component of an interdisciplinary design.
8. Netweaver was developed by Michael Saunders of Penn State University, and Bruce Miller, Rules of Thumb, Inc., Erie, PA.
9. We are grateful to Mark Zollinger, Environmental Systems Research Institute, Redlands, CA for his expert advice and guidance in this process.

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