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Earthquake Impacts on the Urban "System of Systems"

**Author(s):** Sudha Maheshwari , Eric Jones , Steen Rasmussen  
Los Alamos National Laboratory, Los Alamos, NM

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**Urban Security Initiative:**  
**Earthquake Impacts on the Urban "System of Systems"**

**Authors: Sudha Maheshwari<sup>1</sup>, Eric Jones<sup>2</sup>, Steen Rasmussen<sup>3</sup>**  
**Los Alamos National Laboratory, Los Alamos, NM**

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Sudha Maheshwari  
at  
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Applications of Remote Sensing and GIS for Disaster Management

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<sup>1</sup> MS D450. Los Alamos National Laboratory, Los Alamos NM 87545 U.S.A. and Rutgers University, Edward J. Bloustein School of Urban Planning and Policy Development, NJ 08901.  
sudha@eden.rutgers.edu

<sup>2</sup> MS D450. Los Alamos National Laboratory, Los Alamos NM 87545 U.S.A. honais@lanl.gov

<sup>3</sup> MS D407. Los Alamos National Laboratory, Los Alamos NM 87545 U.S.A. and Santa Fe Institute,

## **Introduction**

Large cities represent the ultimate dichotomy in the relationship between human beings and environment. On the one hand they provide concrete testimony of the power of humans in changing the natural environment. On the other, a natural disaster in a large city clearly demonstrates how defenseless human beings can be when nature decides to lash its whip in the form of a merciless earthquake, hurricane, or flood. This has been a recurring phenomenon in recent years as losses of life and property due to disasters in large urban areas, in both the developed and developing world, has escalated beyond what one had ever comprehended. Large cities also represent the contradictions of providing economic, social, and cultural opportunities as well as creating vulnerabilities to large disasters. As cities attract more people, they also increase the disaster loss potential by concentrating people and investments in a small spatial extent. Therefore, the interplay between cities and disasters provides an interesting example of the age-old topic of the relationship between human beings and nature.

This paper is a discussion of how to address the problems of disasters in a large city, a project titled Urban Security Initiative undertaken by the Los Alamos National Laboratory. The paper first discusses the need to address the problems of disasters in large cities and then provides a framework that is suitable to address this problem. The paper then provides an overview of the module of the project that deals with assessment of earthquake damage on urban infrastructure in large cities and an internet-based

approach for consensus building leading to better coordination in the post-disaster period.

Finally, the paper discusses the future direction of the project.

### **Why Cities?**

Large cities are becoming more and more common due to the heavy movement of population from rural areas into cities, particularly in the developing world. Even in the developed world, including the United States, large cities are still very popular in spite of urban flight and increasing suburbanization. It has been estimated that there are more than 300 cities with population greater than a million worldwide and most of this growth has taken place in the last 50 years. The United Nations estimates that by the year 2025, 61% of the world's population will be living in cities and there will be 28 "giant metropolitan complexes" of over 8 million people<sup>4</sup>. The trend of rapid urbanization is not without repercussions for the social, physical, and environmental fabric of the cities. Problems of insufficient and inefficient infrastructure, population growth in marginal lands, increased competition for limited resources and environmental problems such as air, water, and noise pollution accompany most urbanization processes. This affects the normal functioning of the cities, let alone their capacity to cope with catastrophic events. Added to this is the fact that many large cities of the world are located in geophysically hazardous areas such as floodplains, seismically active areas, coastal areas, and cyclone/hurricane prone areas. A study by Degg<sup>5</sup> shows that about 78% of the world's

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<sup>4</sup> United Nations Center for Human Settlements (HABITAT). 1996. *An Urbanizing World: Global Report on Human Settlements 1996*. Oxford University Press.

<sup>5</sup> Degg, Martin. 1992. *Natural Disasters: Recent Trends and Future Prospects*. Geography.

100 most populous cities are exposed to at least one of the following hazards:

earthquakes, tsunamis, volcanoes, and windstorm. About 45% are exposed to more than one of the above hazard type. This analysis does not take into account hazards of flooding which could increase the above numbers significantly.

The recent past provides ample evidence of the increasing threat of disasters that confront large cities. Between 1945 and the present, about 100 natural disasters have afflicted large cities. Among these are: Nagoya, Japan (earthquake), Tangshan, China (earthquake), Bucharest, Romania (earthquake), Adelaide and Melbourne ,Australia (bushfires), Mexico City, Mexico (earthquake), Dhaka, Bangladesh (floods), Oakland, USA (fire), Miami/Dade County, USA (hurricane), Los Angeles, USA (earthquake), Cairo, Egypt (earthquake), and Kobe, Japan (earthquake). Not only does a disaster represent substantial economic losses for the city and it's hinterland, it often affects the national economy of the country significantly. With the current trend of globalization and interconnectedness of economies, the impact of a disaster affecting a large city is seldom confined to that city alone. Ripples of its effect can be felt in the world economy. For example a large earthquake in Los Angeles or a large hurricane in New Orleans would definitely have an impact well beyond the geographic hinterland of the concerned city.

The question that may be posed is - what is it that makes disasters in large cities different from disasters in smaller communities or in rural areas? Features of disasters in large cities pose entirely new problems for disaster management as compared to smaller

communities<sup>6</sup>. The high population density, complex societal mix, large income gap, abject poverty, and a large informal sector associated with most large cities, lead to a complex intermingling of cause and effect. Not only do large cities pose special problems for the delivery of emergency response services, but recovery in most cities is slow owing to the greater vulnerability of infrastructure networks or what may be termed the lifelines of the city<sup>7</sup>. The concentrated but distributed functionalities such as food, power, transportation, etc all depend on high tech infrastructure that breaks down at the time of a disaster and paralyzes the city.

### **The Problem**

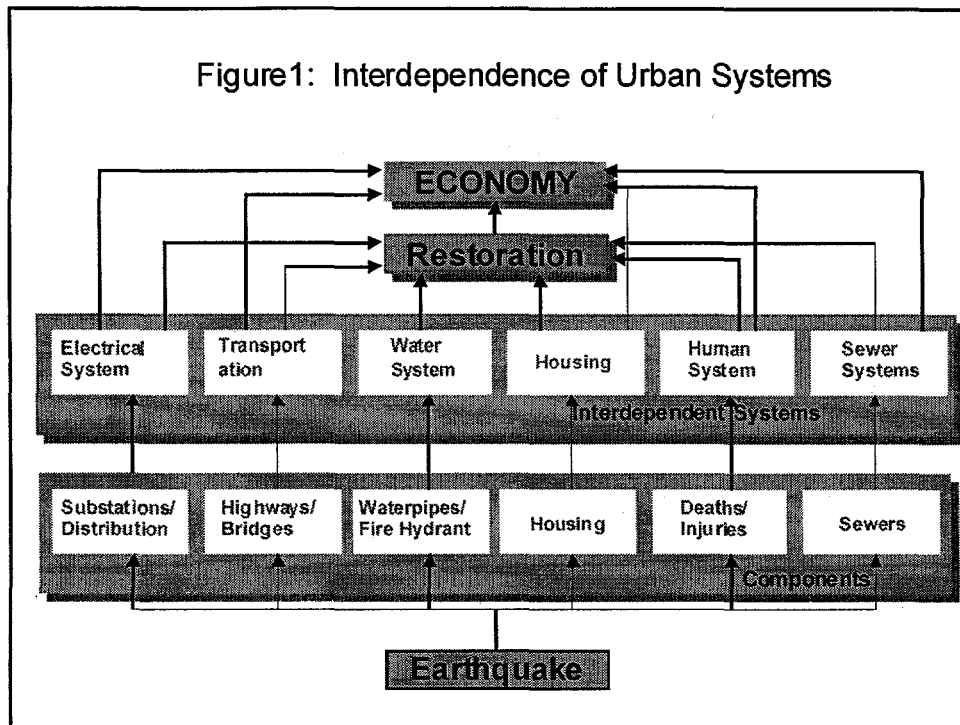
It is important to further the discourse on disasters in large cities and to understand the problems associated with addressing the impact of disasters in large cities. An important aspect of this is to understand the interactions between various urban systems such as transportation, electrical generation-and-distribution, housing, water systems and so on. A vital aspect of this is to understand how damage in one or more of these systems can affect the recovery of the city as a whole after a disaster (Figure 1).

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<sup>6</sup> Mitchell, James K. 1995. Coping with Natural Hazards and Disasters in Megacities: Perspectives on the Twenty-first Century. *Geojournal*. v.37 n(3).

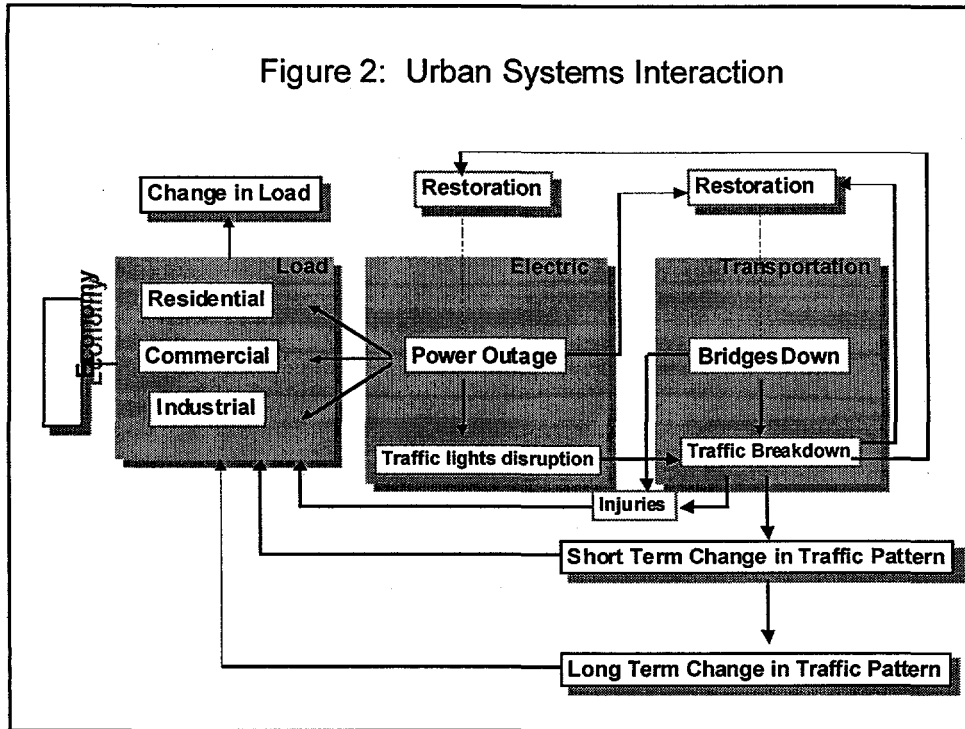
<sup>7</sup> Mitchell, James K. 1995. Coping with Natural Hazards and Disasters in Megacities: Perspectives on the Twenty-first Century. *Geojournal*. v.37 n(3).





The damages of components of one of the systems can not only affect that system, but can have a significant effect on the other systems as well. This slows recovery and delays the return to normal functioning of the entire system. For example, the collapse of a particular component in an electrical substation can lead to electrical outages that can cause disruption of traffic lights leading to breakdowns in traffic flow and to accidents. This breakdown of the traffic can in turn lead to delays in restoration of the electrical systems. Further, both the delays in the restoration of electrical systems and in the breakdown of traffic can affect the economy of the urban area significantly. An example of the interaction of the various components across different systems is illustrated in Figure 2. This interaction leads to a “system of systems”, the understanding of which is crucial to addressing the problems of disasters in large cities.

This interrelationship between the various interconnected systems is essentially lacking in most of the studies on disaster infrastructure damage.



An understanding of disasters in large urban areas from a systems perspective is beyond the scope of a single discipline. Hence a multidisciplinary approach is required involving integration of knowledge from disciplines such as urban planning, geology, seismology, electrical engineering, civil engineering, transportation, volcanology, sociology, demographics, etc. Each of these disciplines addresses problems of importance for an understanding of disasters in large cities and has its own priorities and models for this purpose. For example, the urban planners may focus on land use and its effects on disaster mitigation or on the role of people and community-building in disaster management. The seismologists, hydrologists, volcanologists, and other physical scientists analyze and model the physical phenomenon that leads to the disaster.

Likewise, the electrical engineers, transportation engineers, civil engineers are concerned mostly with the vulnerability of individual systems and how damage to other systems can affect their own system. To address the problems of disasters in large cities realistically, it is essential to integrate the knowledge base and models existing in each of these disciplines.

Recent advancements in computing technology, visualization and studies of complex systems and non linear science<sup>8</sup> and the insights from the various disciplines offer tremendous potential to understand the interactions of urban systems for the purpose of planning and mitigation. At present, while there are software that to some extent incorporate such interactions in doing damage assessments, they fall short of providing a detailed picture of the intricacies of such interactions. For example, HAZUS<sup>TM</sup><sup>9</sup>, a software package for earthquake damage assessment sponsored by Federal Emergency Management Agency and National Institute of Building Science, models each of the systems separately without understanding the inter-relationships between the systems. Also, it approaches the problem at a highly aggregated level and is thus more suitable when it is used to assess damages to large areas at the multi-county level.

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<sup>8</sup> Since we and others are in the process of developing usable methods for applications there is no single, coherent reference to this new and very active research area. A general introduction to the area of complex systems and nonlinear science may be found as past and ongoing activities (and conferences) at Center for Nonlinear Studies at Los Alamos National Laboratory (<http://cnls.lanl.gov>) and at the Santa Fe Institute (<http://www.santafe.edu>). Examples of how these concepts may be used to address urban and other socio technical issues include transportation (<http://transism.tsasa.lanl.gov/>) and urban security ([http://www.ees.lanl.gov/EES5/Urban\\_Security/](http://www.ees.lanl.gov/EES5/Urban_Security/)). See also e.g.: Environment and planning B, 1997, 24(2) March, pp 159-316 (Special issue: Urban systems as cellular automata), Self-organization of complex structures: From individual to collective dynamics, Ed. Frank Schweitzer, Gordon and Breach Sci Pub. 1997, and Nonlinear dynamics, mathematical biology, and social science, Joshua M. Epstein, Lecture Notes Volume IV, Studies in the Science of Complexity, Addison-Wesley, 1997.

<sup>9</sup> FEMA 1997. Earthquake Loss Estimation Methodology HAZUS<sup>TM</sup>. User's Manual.

However, it has been seen in many disasters in large urban areas such as the Northridge earthquake of 1994, that non-uniform settlement patterns and geologic factors can produce discrete, highly localized clusters of serious damage. The effects of the damage may also be concentrated within particularly sensitive infrastructure network such as the highway network, the electrical distribution network, or the water and sewer networks.

Although the damaged locales and affected infrastructure systems are not independent of the larger urban areas and systems of which they may be a part, decision-making often takes place at the level of relatively smaller geographical units or at the level of a specific infrastructure system. Therefore, while broad-area damage estimation models are of considerable utility, they are not very suitable for application to the complexity found in most large cities. Therefore, it is equally important to develop and use models with which damage estimates can be made for individual infrastructure components and assess the operational capabilities of the damaged locales and systems. The detailed study of the individual systems and their interrelationships with other system is very useful for managers of these systems. Hence it is essential to understand the inter-linkages of different systems and their impact, a capability presently lacking.

Further, it is important for emergency personnel from the various infrastructure systems and other stakeholders (such as community organizations, NGOs, etc.) to talk with one another and understand how problems in other systems can affect their own system. Not only this, it is very crucial for other stakeholders (such as local governments, community organizations, NGOs, international agencies like Red Cross, and other relief agencies) to understand the process of recovery of these systems and how

they may affect their own capabilities. At present, the coordination amongst various stakeholders is done in an ad hoc manner in the aftermath of a disaster. In the melee following a disaster, it is not surprising that there is considerable confusion, conflict and duplication of efforts. This can largely be avoided if the different stakeholders were to understand each other's objectives, problems, priorities and limitations prior to the disaster. Consensus building exercises with various disaster scenarios can largely improve the relief and recovery efforts of the various agencies and stakeholders in this regard.

Thus, it is important not only to model the damage due to earthquakes to the individual infrastructure systems, but also to understand the inter-relationships between various systems. Further, it is crucial to devise processes that can lead to better coordination and understanding amongst the various stakeholders involved in disaster recovery.

### **Urban Security Project**

The Urban Security Project at the Los Alamos National Laboratory aims to model the city based on the above-discussed inter-relationships of the various urban infrastructure systems. The Los Alamos National Laboratory is a pioneer in many methods and models dealing with the physical aspects of geophysical events and infrastructure risk assessment, which can be easily adapted for urban regions. Furthermore, with the laboratory's advanced computing capabilities, integration of various computing and data intensive models can be accomplished. The project is designed to analyze the effects of disasters, both natural and human-induced, on the urban

infrastructure systems and their inter-linkages to focus on emergency response issues, mitigation issues, the recovery process, and the return to normal functioning of the city as a system. Many of the description of infrastructure systems and of pertinent geophysical processes are based on Geographic Information Systems (GIS) or lend themselves very favorably to GIS given the data capture, analysis and synthesis, and visualization functionalities of GIS. Hence the integration of the various models and data required for these models will be done under a GIS framework. The purpose is the integration of modeling system consisting of legacy code components written in different languages, installed on different hardware platforms using JAVA and CORBA, an Object Request Broker (ORB). This combination allows communication among objects written in different languages across address spaces and networks and adhering to the seven design criteria: (1) Extensible, (2) Distributed, (3) Multi-user, (4) Parallel, (5) Secure, (6) User friendly, and (7) Easily Implemented. Links between the physics based models will be made to decision-making tools. The data and visualization tools will be provided to the end-users via servers in a distributed environment.

Los Angeles has been chosen as the prototype city for the purposes of modeling for obvious reasons. It is a city where the threat from earthquakes is a real one. Further, the city comprises of many socio-economic, cultural ethnic groups making disaster recovery very unusual. The heavy investment in infrastructure systems, and the vast repercussions (on the local and global scale) of the breakdown of these systems in Los Angeles also makes it an ideal case city. Moreover, the city is committed to disaster

mitigation and planning such that any effort in this direction will be directly useful to the managers and planners of the city.

### *Modeling the Electrical Power Infrastructure*

Commercial infrastructures are a necessary piece of urban security. These infrastructures include communications, transportation, water and sewer, and power and energy networks. Recent policies of the United States Government have taken action to ensure the security of many commercial infrastructures, and emphasize the importance of these infrastructures to the nation's well being<sup>10</sup>. The electric power infrastructure is particularly important since almost every activity in modern urban environments is dependent on it for proper functioning. Electricity is important for lighting, heating, ventilation, air conditioning, communications (radio, television, etc), vehicular and air traffic control, and virtually all control systems, the proper operation of emergency facilities like hospitals, command and control centers, commercial and industrial processes. The loss of electricity, even over short periods, can cost billions of dollars to the US economy. Therefore, a section of the Urban Security project deals with the analysis of earthquake impacts on the electrical power systems of the City of Los Angeles.

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<sup>10</sup> President William J. Clinton, Executive Order, "Critical Infrastructure Protection, Executive Order 13010," Federal Register 61, no. 138 (17 July 1996): 37347. and President William J. Clinton, Presidential Decision Directive, "Critical Infrastructure Protection: Sector Coordinators, Presidential Decision Directive 63," Federal Register 63, no. 150 (5 August 1998): 41804.

In this phase the project aims to understand the effects of three scenario earthquakes in the LA Basin: (1) a magnitude 6.75M on Elysian Park fault running directly under downtown LA, (2) a 7.75M on the San Andreas Fault, and (3) a replication of the Northridge earthquake. The hypothetical Elysian Park event would be likely to cause significant damage in downtown Los Angeles, thereby causing a dramatic loss of electric load, whereas the San Andreas event is likely to knock out the supply. Analysis of the Northridge earthquake and its effect on the electric system provides a means of calibrating the methodology. The modeling of all three events will provide decision-makers and policy-makers with insights of how to manage similar events and how limited resources should be used for planning. The three-scenario study will also help in analyzing patterns of damage if any.

One of the most important aspects of understanding the effects of earthquakes is to predict the resultant ground motions due to the earthquake with a high degree of reliability. The distribution of ground motion in real earthquakes is often very non-uniform and consequently the distribution of damage is also non-uniform. With this in mind, the methodology for this project utilizes first-principle simulations of the earthquake ground motions that take into account details of the subsurface geology, particularly important in basin settings. It also includes the important effects of surface sediments. Generally, ground motions with significant energy content at frequencies of 3 Hz and greater damage the components of the various urban infrastructure systems.



Current simulation methods are restricted to frequencies below about .5 hertz<sup>11</sup>. Methods currently being developed for use on the Los Alamos high-performance computers will eventually allow simulations at frequencies of interest. In the early stages of the project, approximations of higher frequencies ground motion are being used.

Electricity is generated at large, centralized generating stations where energy sources such as coal, natural gas, hydrodynamic potential, nuclear fuel, wood, or solar radiation are converted to electrical energy. Electricity from generating units is transformed to very high voltages for efficient transmission through a vast network of transmission lines. Transmission lines interconnect generating stations to substations, where voltage is reduced for local distribution and ultimate delivery to individual customers. To model the susceptibility of the electrical network to damage at a level of detail that can be useful to the emergency managers and decision-makers, it is essential to understand the fragilities at the sub-component level of all the electrical system components, namely substations, generation plants and distribution network. While HAZUS<sup>TM</sup><sup>12 13</sup> models the individual fragilities of substations, generation plants and distribution networks as a composite, this level of detail is not enough for a detailed analysis of electric power failure modes. What would be more useful is to understand the failure of the entire set of substations or distribution networks based on the fragilities of individual components that make up these units. This allows an analysis of the

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<sup>11</sup> Olsen, Kim B. and Ralph J. Archeluta. 1996. Three Dimensional Simulation of Earthquakes on the Los Angeles Fault System. Bulletin of the Seismological Society of America. v. 86, no. 3 pp. 575-596.

<sup>12</sup> Earthquake Loss Estimation Methodology HAZUS<sup>TM</sup>. User's Manual.

consequences of the collapse of individual units. With using cellular automata models, the propagation of damage to electric supply can be modeled<sup>14</sup>. Thus, the collapse of a substation can propagate failure of another connected substation or distribution, as was seen in the recent power outage in San Francisco.

Capabilities of this nature will be very useful for the electrical network management, as this effort will demonstrate the vulnerable nodes within the network. Furthermore, it can be useful in generating scenarios of damage for training exercises for emergency personnel for these infrastructure systems. This effort can also be taken further to assist policy makers and planners in their effort to mitigate losses due to disasters. Thus, the various scenarios can reveal patterns of damages and electrical knockouts based on various factors. This information can be combined with information on socio-economic characteristics to provide policy makers with suitable measures for mitigation. For example, a pattern analysis may reveal areas that are susceptible to electrical outage. Some of these may be areas where businesses are not likely to be able to afford insurance or individual back-up power. Therefore, it may be important to come up with other mitigation measures such as community shared small power generators as back-up or devising ways of making these electrical infrastructures less vulnerable.

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<sup>13</sup> Earthquake Loss Estimation Methodology HAZUS<sup>TM</sup>. User's Manual.

<sup>14</sup> The project is in the process of acquiring data from the LA WPD on the substations at the 34.5 kV level. Besides getting the location and other characteristics of these substations, the project is also getting data on the connectivity of these substations to model the propagation of damage.

## *Consensus Building*

Since such mitigation strategies are important, it is also necessary to bring to the table the advantages, problems and limitations of the various options for consensus between all stakeholders. This would also help build better understanding between stakeholders and hence better coordination in the relief and recovery phase of a disaster. To facilitate the disaster planning process, we propose to develop an Internet-based environment that allows multiple organizations to solve collective challenges that are not approachable from the level of the individual<sup>15</sup>. This will involve the combination of the understanding of the self-organizing societal dynamics with self-organization on the Internet. It has been shown that the Internet, capable of reaching thousands of individuals independent of space and time, provides a valuable tool for reaching consensus. Consensus among the many stakeholders in Los Angeles on how to best organize disaster relief and implement suitable mitigation strategies for a major earthquake can likely be reached in a faster, less expensive, and more efficient way by using the Net capability. This part of the project will be an experiment to test this. The project will bring together various stakeholders involved in disaster planning to participate in this experiment that will consist of an Internet-based environment consisting of three parts as described in

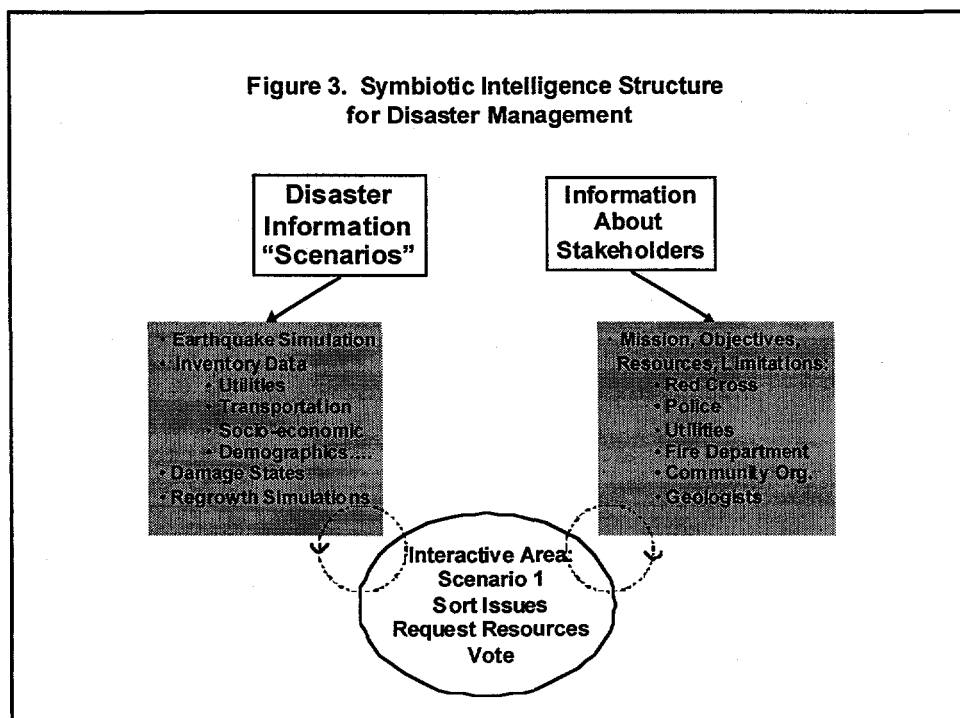
Figure 3:

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<sup>15</sup>Rasmussen, Steen and Johnson, Norman. 1998. Self-organization at and around the Internet". Invited plenary presentation at the 6th International Conference on Chaos and Complexity in Manufacturing, Santa Fe NM, March 31 - April 3, 1998. Technical report LA-UR 98-2549 (12 pages). and Johnson, Norman, Steen Rasmussen, Cliff Joslyn, Luis Rocha, Steven Smith and Marianna Cantor. 1998. Symbiotic Intelligence: Self-organized knowledge on distributed networks, driven by human interaction. Artificial Life 6, eds. C. Adami et al., MIT Press (1998), pp 403-407. Technical report LA-UR 98-489.

- (i) Detailed scenario data from earthquake simulations together with damage estimates from different potential earthquakes.
- (ii) Information about mission, mode of operation, resources, needs, limitations, and priorities of each of the stakeholders involved.
- (iii) An interactive area where each stakeholder can sort disaster planning issues according to importance, order necessary actions in time sequence, request resources, and the like. This information given by each stakeholder organization will be allowed to interact with other stakeholder's information through voting and other means.

A given disaster scenario will be generated through the first part of the project such that all the stakeholders refer to the same data. All stakeholders will be requested to



review the scenario in detail from their home organization within a given time period.

They will then be requested to sort the disaster planning issues in area (iii) above based on the detailed scenario. This information provided by the various stakeholders will be allowed to interact with the information provided by the other stakeholders through voting, summation, etc. after a set time period. The resulting potential conflicts will be picked up by the Internet system and clearly provide evidence of resource bottlenecks, conflicting priorities, etc. and it will also be clear when consensus emerges. It will be easy to see which stakeholders are competing for resources such as helicopter, power, etc. and which stakeholders are converging on certain issues. This process can be iterated several times and it is expected that as a greater "systems" understanding evolves amongst the various stakeholders, consensus will be reached. To resolve the conflict, it is essential to understand not only "who" is at conflict but also "why". The knowledge gained can be used to shape discussions at more traditional (non-Internet) stakeholder committees as this Internet-based consensus building and decision support system is not proposed to substitute existing means of communication between stakeholders. Rather it is meant to supplement existing tools in order to facilitate a mutual understanding of the different organizations needs and thus result in better disaster preparedness.

### **Future Aims**

In future, the project envisions to model various individual systems, particular the vulnerability of the transportation network, housing, sewer and water networks to

earthquake damage. The next step would be to understand the interaction between these networks and individual systems and start to model the interdependency of the various systems. Another part of the Urban Security Initiative is involved in linking models that deal with urban ground water, plume dispersion, and the nitrate cycle. These models will eventually be linked with the infrastructure damage models. Thus, the aim is to create an understanding of what would happen if a facility storing toxic waste, or a gas main, or sewer pipes were to be damaged in an earthquake. This would help understand the true impact of an earthquake, not only in terms of the breakage of one of these components, but in the resultant long-term effect of the breakage on urban life itself.