Assessing the Role of Lifeline Systems in Community Disaster Resilience

by Stephanie E. Chang and Christopher Chamberlin

Research Objectives

The objective of this research is to advance the state-of-the-art of disaster loss modeling, with particular emphasis on understanding how mitigating lifeline infrastructure systems can improve the disaster resilience of a community. A model will be developed that focuses on direct social and economic losses. It will be applied to the Los Angeles Department of Water and Power (LADWP). Key advances in this model will include evaluating lifeline-related losses within the broader context of the disaster, and developing a socio-economic loss model that is agent-based.

Urban infrastructure systems such as water and electric power networks provide critical services to all sectors of a community. Evaluation of alternative seismic upgrading strategies for these systems should therefore take into account not just the utility provider's own costs and benefits, but the potential impacts on the community as a whole. In this context, MCEER researchers have proposed the concept of "community disaster resilience" as a framework for evaluating and comparing loss reduction strategies (Bruneau et al., 2003). This paper addresses a central question in the resilience framework: how to evaluate the benefits of lifeline mitigations for disaster resilience of the entire community.

This effort builds on research in previous years that focused on the water and electric powers systems serving Memphis, Tennessee. Prior research developed integrated engineering-economic loss estimation models (Chang et al., 2002; Shinozuka et al., 1998), explored the relationship between loss estimation and resilience modeling, and applied the resilience approach to an analysis of alternative seismic upgrading strategies for the Memphis Light, Gas and Water Division (Chang and Shinozuka, 2004).

Currently, the Memphis model is being transferred with major enhancements to a case study of the Los Angeles Department of Water and Power's (LADWP's) systems. As described in the current paper, a key enhancement is the setting of lifeline outage impacts in the context of other earthquake damage (e.g., to buildings), which provides a more realistic and accurate assessment than modeling lifeline outages in isolation. Another important modification consists of the shift from an area-based to an agent-based model

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Research Team

***Stephanie E. Chang**, Assistant Professor, School of Community and Regional Planning, University of British Columbia; formerly of the Department of Geography, University of Washington, and **Christopher Chamberlin** and **Enru Wang**, Graduate Students, Department of Geography, University of Washington*

Other MCEER Team Members

***Rachel Davidson** and **Thomas D. O'Rourke**, School of Civil and Environmental Engineering, Cornell University*

***Adam Rose**, Department of Geography, Pennsylvania State University*

***Masanobu Shinozuka**, Department of Civil and Environmental Engineering, University of California, Irvine*

***Kathleen Tierney**, Natural Hazards Research and Applications Information Center, University of Colorado, Boulder*

Previous Summaries

1999-2000:
Chang et al.,
http://mceer.buffalo.edu/publications/resaccom/9900/Chapter1.pdf

structure. Economic impacts are now evaluated at the level of the business, rather than the census tract. This approach affords modeling advantages in terms of scalability, ease of simulation, validation capability, and consistency with underlying empirical data. This paper describes progress to date on the Los Angeles resilience model. The principal areas of progress are development of a multi-source economic loss model, derivation of a business sample for simulation, and software implementation.

Multi-Source Economic Loss Model

Figure 1 provides a schematic diagram of the community resilience model (blue box) and its relationship to the overall MCEER study of LADWP systems. For a given scenario earthquake, the community resilience model evaluates economic impacts, social impacts, and resilience outcomes. Key inputs from MCEER engineering investigators include the availability of water and electric power for spatial units (e.g., census tracts, electric power service areas) at various points in time following the earthquake. The status of buildings is assessed using the Federal Emergency Management Agency's (FEMA's) HAZUS loss estimation software.

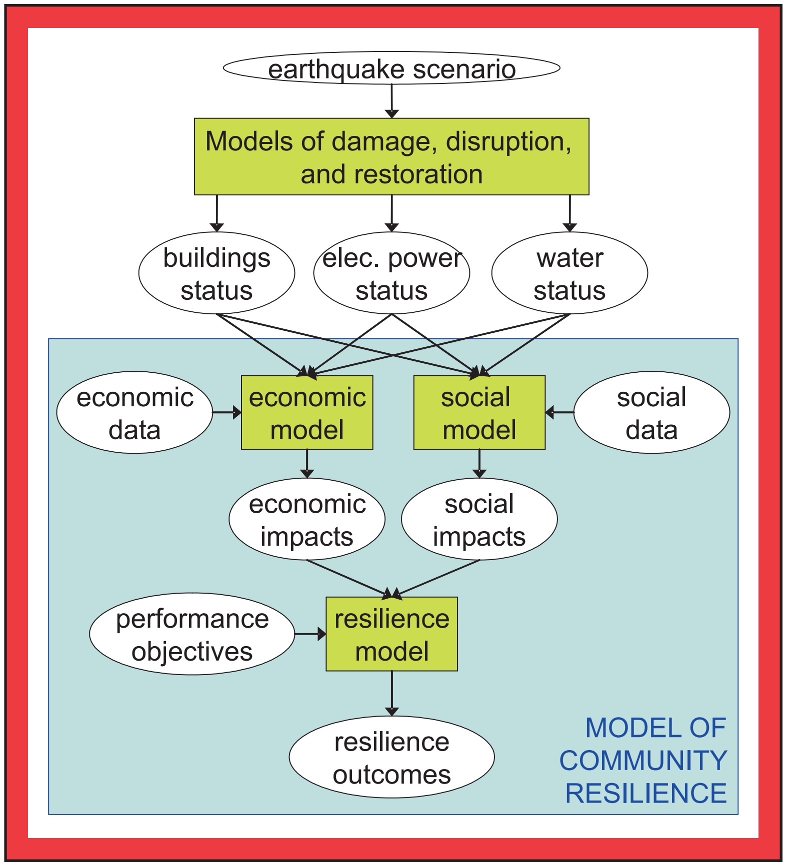
The simultaneous evaluation of economic disruption from loss of building, water, and electric power is an important advance. It avoids the potential inflation of losses attributable to any of these sources individually. For example, a business may be unable to operate if it loses either water or electric power. Suppose it loses both in an earthquake. Evaluating water and electric power impacts simultaneously, rather than separately (as is the case with most current models), ensures that this business's losses will not be counted twice. This enables a more accurate assessment of potential losses, as well as potential benefits of lifeline mitigations.

Data to develop and calibrate the multi-source economic loss model were obtained from two large business surveys conducted by K. Tierney and colleagues at the Disaster Research Center of the University of Delaware following the 1989 Loma Prieta and 1994 Northridge earthquakes. Together, these surveys include over 2,000 businesses in the Santa Cruz and Los Angeles areas. Here, we used data from survey questions on sources of disruption (e.g., whether the business lost electric power), the associated levels of disruptiveness

The primary users of this research are intended to be utilities, as well as local emergency managers and planners. This research addresses the questions of how utility losses in earthquakes will affect the community as a whole, and how seismic mitigation of utility infrastructure would improve the community's resilience to future disasters.

(e.g., "very disruptive"), whether the business closed temporarily, for how long, and the major reasons for this closure.

Based on these data, a three-step model was developed in which losses are evaluated for each business in the simulation. The first step involves determining the degree of building damage, water loss, and electric power outage suffered, primarily on the basis of the business's location in the study area. The second step translates these physical losses into disruptiveness to the business's activities. Disruptiveness is measured according to the qualitative scale used in the Loma Prieta and Northridge surveys. Table 1 shows the probabilistic model that relates water outage to business disruption. As shown in the table, outage is more likely to be disruptive for businesses in some industries, such as health services, than for others. For a particular business, a deterministic disruptiveness state is assigned using Table 1 and a random number generator. Similar tables (not shown) were also developed for building and electric power loss.



■ Figure 1. Schematic of Community Resilience Model

■ Table 1. Probability of Disruptiveness Level due to Water Outage

Industry	Disruptiveness Level			
	"Not at all disruptive"	"Not very disruptive"	"Disruptive"	"Very disruptive"
Agriculture	8 %	15 %	42 %	35 %
Mining, construction, transportation, communications, utilities	8 %	31 %	37 %	24 %
Manufacturing	0 %	35 %	26 %	39 %
Wholesale and retail trade	10 %	23 %	26 %	41 %
Finance, insurance, real estate	5 %	24 %	29 %	43 %
Health services	2 %	6 %	22 %	70 %
All other services	7 %	29 %	24 %	41 %
ALL INDUSTRIES	7 %	25 %	27 %	42 %

Note: Row sums may not add to 100% due to rounding error.

■ Table 2. Probability of Business Closure

Case	Number of sources in each disruptiveness category				Probability of closure
	"Not at all disruptive"	"Not very disruptive"	"Disruptive"	"Very disruptive"	
A				2+	90%
B			1+	1	80%
C			0	1	63%
D			1+	0	54%
E		1+	0	0	30%
F	3	0	0	0	0%

The third step translates business disruption into economic loss. For each business, the disruptiveness levels from buildings, water, and power are tallied and related to a probability of temporary business closure, as shown in Table 2. For example, a business that experienced "very disruptive" electric power and water outage, as well as "not very disruptive" building damage, would be considered Case A in the table and assigned a 90% probability of closure. The closure probabilities are translated into deterministic closure states using a random number generator. Note that this economic disruption model is evaluated at multiple timesteps (e.g., at weekly intervals) until the business reopens.

Initial results of the economic impact model include the duration of closure (if any) for each business in the simulation. These results are then scaled up to the industry level for the entire study area and translated into dollar losses. For this purpose, it is assumed that a business produces no output while it is temporarily closed, and normal output when it is open. Note that this evaluation is currently limited to only direct business disruption loss.

Business Sample

As noted above, economic impacts are simulated at the business level and aggregated to the entire study area. Data from Dun & Bradstreet (D&B) indicate that there are some 372,000 businesses in Los Angeles County, accounting for about 3.4 million jobs. Table 3 shows the distribution by the industry classification used in the model. Note that the vast majority of businesses in all industries are small (i.e., with less than 20 employees). Information on individual businesses is available from Dun & Bradstreet; however, this database is prohibitively expensive. Instead, we obtained an aggregated database with information for each census tract in the county. Data include the number

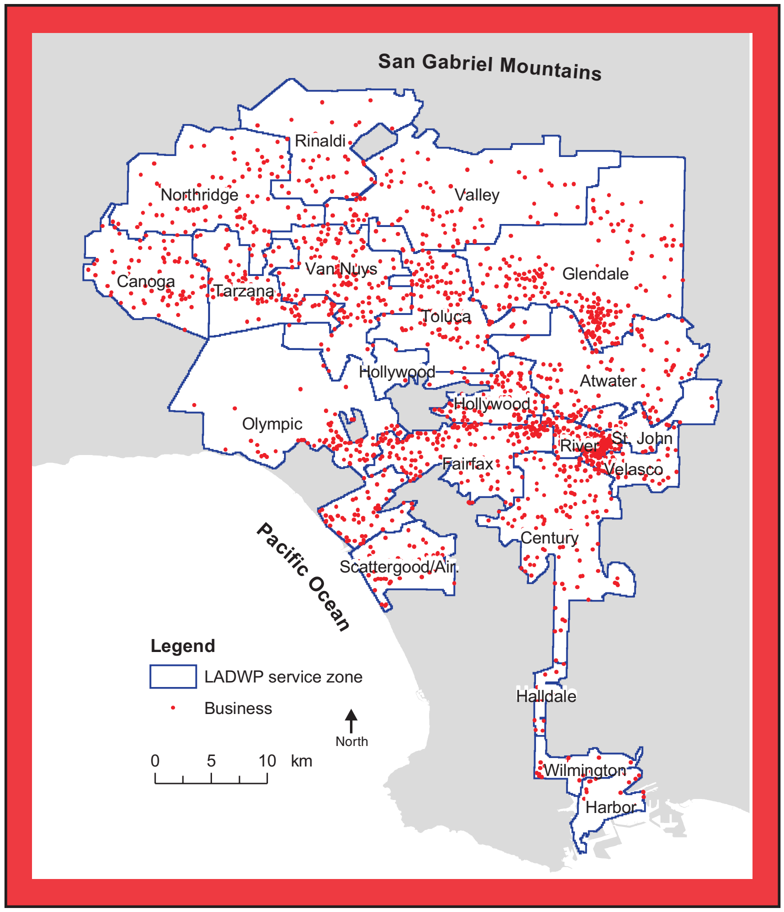
■ Table 3. Businesses and Employment in Los Angeles County

Industry Group	Number of Employees	Number of Businesses	Percent Small Businesses(1)
Agriculture	20,263	3,564	94%
Mining, construction, transportation, communications, utilities	341,594	33,358	91%
Manufacturing	500,045	23,860	79%
Wholesale and retail trade	821,125	105,046	92%
Finance, insurance, real estate	237,697	32,280	93%
Health services	259,578	24,608	94%
All other services	1,222,791	149,675	93%
TOTAL	3,403,093	372,391	92%
Note: (1) less than 20 employees			

Dun & Bradstreet database (December 2003) of jobs and businesses by industry and size class.

From this database, we created a "pseudo-sample" of 3,724 businesses, or 1% of the total population of businesses in Los Angeles County. The Dun and Bradstreet (D&B) database was aggregated from 4-digit Standard Industrial Classification (SIC) codes to the 7-industry grouping shown in Table 2. Each of the 3,724 "business objects" corresponds to a hypothetical business. Each was assigned to an industry such that the sample would have the same industry distribution as the population as a whole. Assigning numbers of employees to the businesses was more complicated since the D&B database only contained aggregate data by business size class. A lognormal curve of business size distribution was therefore generated for each industry, such that it matched the benchmark size class subtotals in the D&B database. Each business object was then assigned a number of employees using the appropriate lognormal curve and a random number generator. Further, for each business subtype, the spatial distribution across census tracts was calculated. Each business object was then assigned a census tract location using the appropriate spatial distribution and a random number generator.

Based on this procedure, a stratified 1% business sample was developed that reflects the total business population in terms of industry, size, and spatial distributions. Figure 2 shows the approximate locations of businesses in the 1% sample, in relation to LADWP's electric power service areas. As noted earlier, the model evaluates



■ Figure 2. Business Sample and LADWP Service Zones

earthquake losses for each business, then scales up to the entire study area. Currently, the study area is LADWP's service territory, which constitutes the majority of Los Angeles County.

Software Implementation

The simulator for the model is implemented in the object-oriented programming language C++. (The earlier loss model of the Memphis water system had been implemented in Fortran.) Each key component of the model has a corresponding object (C++ class) in the simulation software. An object-oriented environment is useful for

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this type of model implementation because it enables clearly defined relationships between the various components, and protects data that should be static from modification.

Further, the C++ inheritance mechanism makes it straightforward to add modified or improved components of the model without affecting the rest of the code. For example, the current model for outage and recovery of water and electric lifelines is very simple. Better empirical data or a more sophisticated model, when available, can be implemented in a class derived from the existing one, which defines the interface to the object used by the rest of the system. Further, it would be possible to mix several implementations of a given component, with different functionality, together in one simulation. The object interfaces make these implementation details invisible to the rest of the simulation.

The overview in Figure 3 shows the major components of the system. Some minor utility classes and the derived implementations described above are not shown. The major components are as follows:

ResiliencySimulator – This is a unique object that contains the rest of the objects for the simulation. The top-level loops for the simulation are here. Because the *ResiliencySimulator* is unable to change the scenario data, these are protected from accidental modification.

Business – This is a basic class that holds data about one business. It holds the business employment size and pointers to the industry and zone the business is in. Results from simulation are stored in *BusinessSimulation*, not here.

Zone – This corresponds to a section of the study area, usually a census tract. It has an ID value and pointers to the lifeline service areas that this zone is contained within. It also contains building damage rates.

WaterArea/ElectricArea – Currently, these objects are identical, but derived classes could implement different models. These objects are capable of returning the lifeline status (available or unavailable) at any given time step.

Industry – This contains data about a given industry group, including the susceptibility to closure due to building or lifeline damage.

BusinessSimulation – This contains the results of simulation for

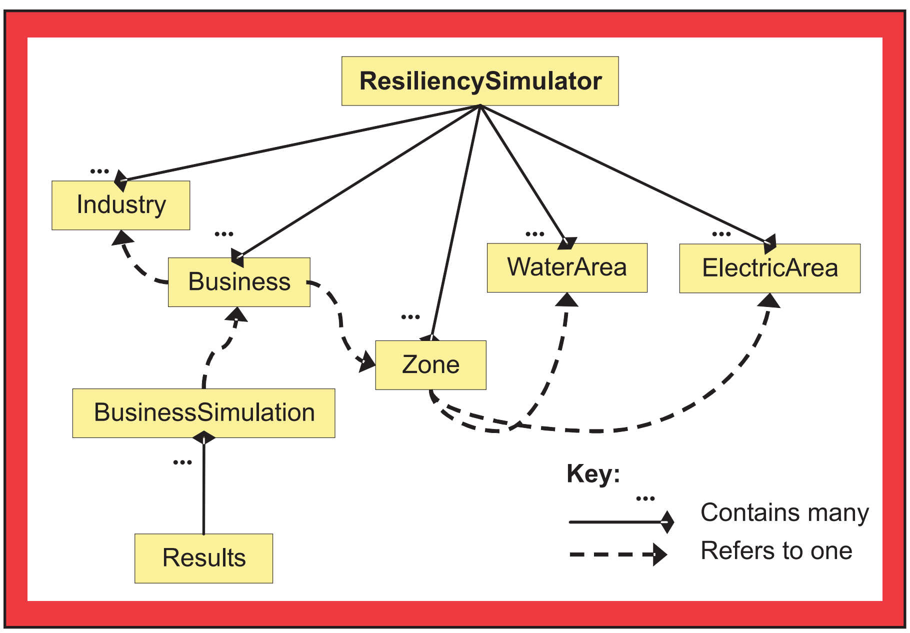

Figure 3. Object Model Overview for Economic Resilience Simulation

one *Business* object, particularly the closure status at given time steps.

Results – This is the top level results object. It contains all of the *BusinessSimulation* objects. After they are computed, code in this object aggregates them and saves the results to disk.

The *Results* objects can be deleted after a run's results are saved without affecting the rest of the data structures, so the simulation is very efficient to reset for another run because the bulk of the data does not need to be recreated. Thus, the multiple runs which are required of this nondeterministic simulator can be executed relatively quickly.

The model uses two types of input data. *Model calibration data* is integral to the calibration of the entire model. Changes here would represent actual changes to the model itself. For example, the *Industry* objects are calibrated for the probability of closure due to building damage, based on empirical surveys. Second, *scenario data* will vary depending on the earthquake scenario being used, such as building and lifeline damage. However, scenario data are static once the simulator starts, because they are part of the unchanging input data for each simulation run. In the simulator, these data are found in classes such as *Business*, *Zone*, and the lifeline areas.

To date, the simulation model has been partially tested for one scenario earthquake, a M7.0 Malibu Coast fault event. This scenario is one (#43) of 47 Los Angeles area events that together have been proposed for probabilistic scenario-based analysis (Chang et al., 2000). Full testing of the model will be conducted when results are available from engineering collaborators on lifeline outages and restoration.

Conclusions and Future Research

Substantial progress has been made in the development of a community resilience model and simulation software. In contrast to an earlier lifeline loss estimation model on which it is based, the resilience model accounts for multiple sources of loss, simulates impacts at the business level, and is implemented in an object-oriented programming language. Efforts to date have focused on assessing economic resilience.

Future research will aim to complete development of the community resilience model. Linkages will be made to other MCEER research on the LADWP case, including indirect economic losses, water and electric power outage, and lifeline restoration. The resilience model will be expanded to address social impacts such as displaced households and disruption to hospitals. Major efforts will also be made to refine the specification of performance objectives – which play a central role in resilience analysis – through stakeholder participation.

Links to Current Research

This effort focuses on the modeling and assessment of earthquake resilience at the community level, with emphasis on economic and social dimensions of resilience. The community resilience model is developed in coordination with other MCEER research on lifeline damage, outage, and restoration (by Shinozuka, O'Rourke, Grigoriu, and Davidson).

Acknowledgements

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