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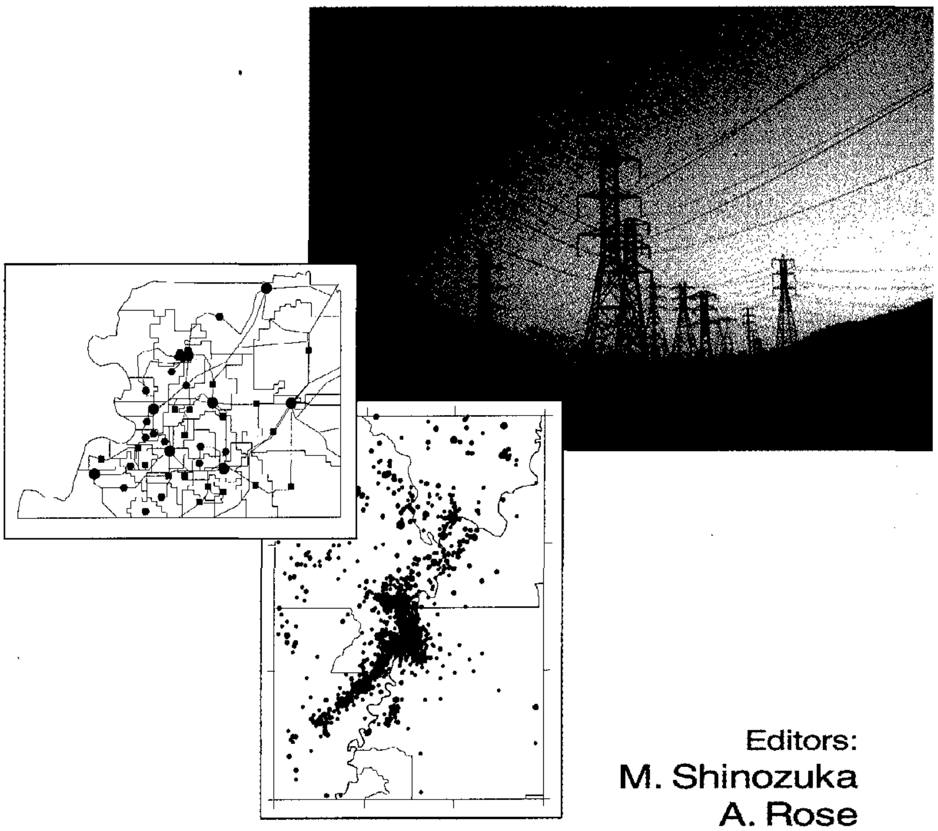
Engineering and Socioeconomic Impacts of Earthquakes

An Analysis of Electricity Lifeline Disruptions in the New Madrid Area



Editors:
M. Shinozuka
A. Rose
R. T. Eguchi

Monograph Series

Multidisciplinary Center for Earthquake Engineering Research
A National Center of Excellence in Advanced Technology Applications

MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

A National Center of Excellence in Advanced Technology Applications

The Multidisciplinary Center for Earthquake Engineering Research

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the State University of New York at Buffalo, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

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This monograph examines the potential effects of a repeat of the New Madrid earthquake to the metropolitan Memphis area. The authors developed a case study of the impact of such an event to the electric power system, and analyzed how this disruption would affect society. In nine chapters and 189 pages, the book is a first of its kind effort to develop and apply a multidisciplinary methodology that traces the impacts of catastrophic earthquakes through a curtailment of utility lifeline services to its host regional economy and beyond. The monographs' chapters include: Modeling the Memphis economy; Seismic performance of electric power systems; Spatial analysis techniques for linking physical damage to economic functions; Earthquake vulnerability and emergency preparedness among businesses; Direct economic impacts; Regional economic impacts; Socioeconomic and interregional impacts; Lifeline risk reduction; and finally, Public policy formulation and implementation.

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Edited by
Masanobu Shinozuka
Adam Rose
Ronald T. Eguchi

MCEER
MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
A National Center of Excellence in Advanced Technology Applications

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University at Buffalo
Red Jacket Quadrangle
Buffalo, NY 14261
Phone: (716) 645-3391
Fax: (716) 645-3399
email: mceer@acsu.buffalo.edu
world wide web: http://mceer.eng.buffalo.edu

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FOREWORD

Earthquakes are potentially devastating natural events which threaten lives, destroy property, and disrupt life-sustaining services and societal functions. In 1986, the National Science Foundation established the National Center for Earthquake Engineering Research to carry out systems integrated research to mitigate earthquake hazards in vulnerable communities and to enhance implementation efforts through technology transfer, outreach, and education. Since that time, our Center has engaged in a wide variety of multidisciplinary studies to develop solutions to the complex array of problems associated with the development of earthquake-resistant communities.

Our series of monographs is a step toward meeting this formidable challenge. Over the past 12 years, we have investigated how buildings and their nonstructural components, lifelines, and highway structures behave and are affected by earthquakes, how damage to these structures impacts society, and how these damages can be mitigated through innovative means. Our researchers have joined together to share their expertise in seismology, geotechnical engineering, structural engineering, risk and reliability, protective systems, and social and economic systems to begin to define and delineate the best methods to mitigate the losses caused by these natural events.

Each monograph describes these research efforts in detail. Each is meant to be read by a wide variety of stakeholders, including academicians, engineers, government officials, insurance and financial experts, and others who are involved in developing earthquake loss mitigation measures. They supplement the Center's technical report series by broadening the topics studied.

As we begin our next phase of research as the Multidisciplinary Center for Earthquake Engineering Research, we intend to focus our efforts on applying advanced technologies to quantifying building and lifeline performance through the estimation of expected losses; developing cost-effective, performance-based rehabilitation technologies; and improving response and recovery through strategic planning and crisis management. These subjects are expected to result in a new monograph series in the future.

I would like to take this opportunity to thank the National Science Foundation, the State of New York, the State University of New

York at Buffalo, and our institutional and industrial affiliates for their continued support and involvement with the Center. I thank all the authors who contributed their time and talents to conducting the research portrayed in the monograph series and for their commitment to furthering our common goals. I would also like to thank the peer reviewers of each monograph for their comments and constructive advice.

It is my hope that this monograph series will serve as an important tool toward making research results more accessible to those who are in a position to implement them, thus furthering our goal to reduce loss of life and protect property from the damage caused by earthquakes.

GEORGE C. LEE

DIRECTOR, MULTIDISCIPLINARY CENTER

FOR EARTHQUAKE ENGINEERING RESEARCH

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PREFACE

BY ADAM ROSE

The potential losses from natural hazards, in terms of both lives and property, are increasing. On the one hand, human action is now so pervasive as to intrude in a major way on the environment, even to the extent of causing climate change. This may manifest itself not only in terms of warming, but also climate variability that increases the prevalence of strong winds and floods. In contrast, our potential to affect the frequency of earthquakes is rather limited. Here the main concern is the other side of the ledger—the continued population and economic build-up, which makes us increasingly more vulnerable even if the frequency of ground shaking does not increase.

Our ability to cope with these issues thus requires an *Integrated Assessment*, ranging from geology and engineering to economics and policy. In-depth studies of this kind are, however, lacking in the earthquake field, and, for the most part, with respect to other natural hazards. Our study is the first that has attempted such an assessment of urban lifeline systems in relation to earthquakes.

This monograph is a first-of-its-kind effort to remedy the situation by developing and applying a multidisciplinary methodology that traces the impacts of a catastrophic earthquake through a curtailment of utility lifeline services to its host regional economy and beyond. The New Madrid Seismic Zone is an appropriate case study because it is the site of the largest earthquakes to hit North America in recorded history. It has been the focal point of extensive research, especially by scientists, engineers, and social scientists affiliated with the National Center for Earthquake Engineering Research over the first ten years of its existence. The study represents the culmination of many of these efforts, which have often involved not only researchers but also public officials, utility managers, company executives, and the public at large.

Our objective is to improve the understanding of the detailed aspects and overall complexity of the problem. This monograph examines and connects the role of an electric utility and its host economy, the vulnerability of the lifeline network to a catastrophic earthquake, the business response to physical damage and production losses, the estimation of direct economic losses, the estimation of indirect losses in the immediate region, and the manner in which these losses cause further ripple effects to a broader metropolitan area and the rest of the U.S., as well as the policy implications of all these interactions. The presentation of this monograph appears multidisciplinary rather than interdisciplinary—it is more like a relay race where each member has picked up the baton from his or her predecessor. However, each hand-off heightens our interdisciplinary understanding of the problem, and the effort as a whole is an integrated assessment.

The ultimate aim of our study is to heighten awareness of earthquake vulnerability and the interconnected nature of human actions. Our methods should help analysts sharpen their vulnerability and loss estimates. It should also help private and public decision-makers make wiser choices about putting themselves at risk and about coping measures ranging from pre-disaster mitigation to post-disaster recovery. Obviously, the analysis is readily generalizable to both other types of lifelines and other natural hazards.

In addition to its practical usefulness, we also take pride as researchers in our ability to advance the state-of-the-art in several areas, both in terms of theory and empirical work. Examples include:

- An advanced vulnerability analysis of a major municipal electric utility system.
- The results of a major survey of perceived business disruptions.
- A GIS overlay of a major socioeconomic database and an electric utility grid, capturing engineering features of electric utility lifelines and their linkages to the economy.
- Neglected features of input-output impact analysis relating to the estimation of indirect effects, general input supply bottlenecks, resilience of production technology to electricity curtailment, and spatial differentials in electricity utilization.

- Formal optimization of scarce lifeline services across sectors and sub-regions.
- A methodology to telescope economic impacts from the neighborhood to the national level.
- A new set of policy recommendations only ascertainable from an integrated assessment.

The number of integrated assessment models of natural hazards is on the rise. A major initiative was recently sponsored by the National Institute of Building Sciences on behalf of the Federal Emergency Management Agency to develop an Earthquake Loss Estimation Methodology, referred to as HAZUS, and related efforts are currently underway to supplement this effort with wind damage and flood damages modules. HAZUS is a computerized system primarily for use by government agencies at all levels to evaluate hazard mitigation, response, and recovery. System components range from ground-shaking through physical damage to the built environment to a translation into direct dollar damage and then direct and indirect business disruption losses. Although HAZUS represents a major advance, for it to be operational it had to sacrifice modeling sophistication of the type presented in this monograph. Also, more specifically, it is very limited in its treatment of lifelines, including only direct physical damage to lifeline structural components. It omits direct impacts on lifeline customers and ensuing economy-wide ripple effects, as well as omitting considerations of optimal reallocation of scarce lifeline resources so as to minimize production and employment losses. We hope that our monograph will prove useful in remedying these omissions in the HAZUS software and other practical approaches to emergency management in the future. At the same time, we intend that our work will provide engineering and socioeconomic insights that will help streamline loss estimation methods for complex systems in general.

This study will prove useful to several categories of readers. While the probabilities of large earthquakes are highly uncertain, the potentially overwhelming economic impacts (both regionally and nationally) cannot be ignored. This study should prove provocative to even experienced public utility managers. It provides compelling evidence for considering a long-term risk management strategy to reduce earthquake vulnerability. Further, it demonstrates the significance of economic impacts induced by lifeline damage and the importance of considering them in designing socially responsible risk management strategies.

Insurance companies might also be interested in our methodologies to quantify indirect losses. There may be a market demand for insurance riders that cover business interruption losses resulting from both direct damage to a facility or building, and from external factors, such as loss of electric power service or unavailability of other inputs. This coverage is not generally offered because of the lack of actuarial experience to assess risk. The methods developed in this study could be used to calculate the potential magnitude of these losses, and then used in establishing a credible insurance structure. As a result, insurance companies might be better able to offer business interruption coverage on a broader basis.

Business executives could gain insight to earthquake preparedness from their counterparts in Memphis in terms of an assessment of vulnerability and identification of coping measures. They might also gain a greater appreciation of the interconnectedness of the economy in which they operate and its ramifications. For example, paying a premium for non-interruptible electricity service may not insure continued operation if a supplier of another critical input opts not to pay the premium and is not able to produce and hence deliver its product.

We also hope that the analysis will be useful to our fellow researchers in the earthquake field, as well as other hazards. We make no pretense that we have exhausted research advances needed to adequately address these issues, and hence encourage others to build on our work.

The research in this monograph has endeavored to improve our perspectives on time and space in relation to hazards. It has imparted spatial dimensions to economic models, where these are usually lacking. This is a key link between the physical world and the human settlement system. On a temporal side, the research emphasis on production losses helps heighten awareness that an earthquake event is not confined to the period of ground shaking and structural damage, but to the longer period during which the socioeconomic system is unable to prevail at pre-earthquake levels. This is key in making the transition from structural to nonstructural (societal) aspects of earthquakes.

Finally, an overall theme of this monograph is that natural hazards accentuate scarcity, thus making resources even more valuable than before. Our limited resources must be balanced wisely between pre-disaster mitigation and post-disaster recovery. Just as emergency medical, fire, and other safety services must be well managed in the aftermath of a disaster, so too should lifeline services. This calls for major reallocations of resources, which may be controversial from a political standpoint. However, our analysis indicates that savings from prioritizing electricity service among those with the lowest intensities of electricity use directly and indirectly (after safeguarding for health, safety, and essential industry) can reduce losses of goods and services several-fold. As the author of one of the chapters notes, not taking advantage of such opportunities results in an outcome as devastating as if the earthquake had actually toppled the buildings in which the lost production would have originated.

Acknowledgments

The papers in this monograph resulted from multi-year, multidisciplinary research sponsored by the National Center for Earthquake Engineering Research. The researchers gratefully acknowledge the assistance of many individuals who contributed to the project. In particular, we would like to thank Dr. Woody Savage, Pacific Gas and Electric Company; Mr. Tom Durham, Central United States Earthquake Consortium; Dr. Anshel Schiff, Stanford University; Dr. Satoshi Tanaka, Kyoto University; and Mr. Tommy Whitlow and Mr. Bill Sipe, Memphis Light, Gas and Water (MLGW) Division, City of Memphis, for their helpful suggestions. We are also indebted to MLGW and the Shelby County Planning Department for access to their data.

We owe a great debt to the staff of the National Center for Earthquake Engineering Research, especially its Director, Dr. George Lee, and its Publication Manager, Jane Stoyle, who did such a fine job during the various stages of this monograph's production. We benefitted greatly from the helpful suggestions of several anonymous reviewers contacted by NCEER to assess the suitability of our manuscript for publication. The financial support of NCEER's sponsors, the National Science Foundation and the State of New York, is also gratefully acknowledged. Several of the authors also benefitted from supplemental finding from related NSF grants and other sources.

Many of the authors benefitted from clerical support at their institutions/organizations. However, the word processing and coordination efforts of Jan Moyer of The Pennsylvania State University deserve special mention.

Perhaps our greatest debt is to our departed friend and colleague, Barclay Jones, who was a stalwart among NCEER researchers for many years. Barclay, perhaps more than anyone, worked to bridge the gap between engineers and social scientists. Without his pioneering efforts, this interdisciplinary monograph would not have been possible.

ABBREVIATIONS

ASCE	American Society for Civil Engineers
ATC	Applied Technology Council
BEPC	(Memphis) Business Emergency Preparedness Council
BSSC	Building Seismic Safety Council
CB	Circuit Breaker
CTPP	Census Transportation Planning Package
CUREe	California Universities for Research in Earthquake Engineering
CUSEC	Central U.S. Earthquake Consortium
DRC	Disaster Research Center
DSS	Decision Support System
EAM	Event Accounting Matrix
EERI	Earthquake Engineering Research Institute
EPRI	Electric Power Research Institute
EPSA	Electric Power Service Area
ESRI	Environmental Systems Research Institute
F.I.R.E.	Finance, Insurance and Real Estate
FEMA	Federal Emergency Management Agency
GAMS	General Algebraic Modeling System
GIS	Geographic Information System
GRP	Gross Regional Product
HH	Household
IMPLAN	Impact Analysis for Planning System
I-O	Input-Output
IRS	Internal Revenue Service
LP	Linear Programming

M	Magnitude
MCEER	Multidisciplinary Center for Earthquake Engineering Research
MLGW	Memphis Light, Gas and Water Division
MP	Mathematical Programming
MSA	Metropolitan Statistical Area
MW	Megawatts
NCEER	National Center for Earthquake Engineering Research
NCGIA	National Center for Geographic Information and Analysis
NEHRP	National Earthquake Hazards Reduction Program
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NMSZ	New Madrid Seismic Zone
NRC	National Research Council
NSF	National Science Foundation
NYSSTF	New York State Science and Technology Foundation
PGA	Peak Ground Acceleration
POLA	Port of Los Angeles
RMS	Risk Management Software
SAM	Social Accounting Matrix
SBA	Small Business Association
SEMS	Standardized Emergency Management System
SIC	Standard Industrial Classification
TAZ	Traffic Analysis Zone
TCLEE	Technical Council on Lifeline Earthquake Engineering
TCU	Transportation, Communications and Utilities
TVA	Tennessee Valley Authority
TVPPA	Tennessee Valley Public Power Association

1

INTRODUCTION

By Adam Rose, Ronald T. Eguchi and Masanobu Shinozuka

The largest earthquakes ever to hit North America were centered in the New Madrid Seismic Zone near Memphis, Tennessee, in 1811-12. Reports of these events were phenomenal. Rivers were rerouted, trees were said to have popped right out of the ground, and the ground shaking itself was felt as far away as Boston (Pinick, 1981; Fuller, 1990). Yet, total dollar damages associated with the earthquakes were probably less than $1 million. The reason is that the area was relatively uninhabited, the city of Memphis, for example, not being founded until several years later.

How would the situation differ today? An earthquake of a similar or even lesser magnitude is projected to be able to cause damage in the billions of dollars. The difference is that the Memphis area is now highly populated and is the center of a sophisticated and highly-interdependent regional economy. Moreover, it is also a major crossroads for the national economy.

Earthquake events are what natural hazards expert Robert Kates (1971) refers to as a "joint interaction phenomenon"—a combination of a physical stimulus and the human settlement system. Both are necessary for disaster to take place. The 1811-12 earthquakes are much like the old philosophical conundrum: if a tree falls in the forest and there is no one around, is there a noise? Similarly, in an area with a small population and little economic activity, an earthquake is not very meaningful.

This is much the rationale for the interdisciplinary nature of this monograph. A study of earthquake impacts requires knowledge of geological origins, but also of the engineering realities of structures and their vulnerabilities, the workings of the economy, the sociology of individuals and organizations, and the politics and planning of mitigation, recovery, and reconstruction.

This monograph presents an integrated study of the implications of an electricity lifeline disruption caused by a major earthquake in the New Madrid Seismic Zone. Scientists do not place a strong likelihood of a reoccurrence of an earthquake the magnitude of the 8.5M event of the previous century in the Memphis area in the near future. Therefore, a 7.5M event was used as the basis for this study. Note that high levels of damage to lifelines and other features of the human use system can take place at even lesser magnitudes as witnessed by the recent Kobe and Northridge earthquakes. The methodology in this monograph, therefore, has more general applicability in terms of earthquake magnitude. In addition, it can provide insights into earthquake impacts in other locations, as well as those stemming from other hazards.

Electricity is one of several utilities termed "lifelines" because of its crucial role in maintaining social and economic systems and because of its linear characteristics, which make it especially vulnerable to disruption from natural disasters. Economic losses stem from direct damage to various parts of an electricity network, including generating stations, distribution stations, transmission lines, and distribution lines. They also result from lost production and sales in those businesses without power, as well as those businesses whose suppliers or customers have had their electricity service disrupted. These impacts can extend far beyond the sites of any physical damage, and, given the Memphis area's increasing role as a major manufacturing and distribution center, may be felt throughout the U.S. economy. Electricity lifelines are also integral to the orderly functioning of society in powering traffic signals, street lights, and safety alarms. These direct disruptions, combined with the loss of jobs in critical goods and services, have the potential to cause civil strife as well.

Society has developed a number of coping strategies for lifeline failures. These include mitigation measures, such as structural reinforcement of electricity network facilities and earthquake resistant equipment. A number of recovery mechanisms also exist, including electricity network exchanges, back-up generation, and conservation. As this study provides information on how an electricity network may be impacted by an earthquake and how this damage spreads throughout the economy, it should prove useful in identifying an improved mix of coping strategies, including nonstructural measures, such as market-oriented and administered reallocation of electricity supplies.

This monograph is the culmination of the efforts of several researchers whose work has been sponsored by the National Center for Earthquake Engineering Research. The team includes geologists, engineers, planners, sociologists, economists, and geographers. The project was undertaken as a *case study*, with a common location, earthquake magnitude, and other parameters used by all the researchers. The study is truly interdisciplinary, as opposed to multidisciplinary. That is, the results from each facet of the research served as a critical input to one or more other facets, and the researchers directly advised or served as collaborators to those in other disciplines. Chapters of the monograph follow a natural progression beginning with the illustration of why electricity is a "lifeline" of the Memphis economy, followed by a spatial characterization of the electricity transmission systems and then by an assessment of its vulnerability to earthquakes. A Geographic Information System (GIS) is used to manage and represent network data. The GIS is key to linking the engineering and economic aspects of the study by effectively subregionalizing the Memphis economy according to electric power service areas. A chapter on individual business response further identifies the importance of electric power in Memphis and the way business copes with its possible disruption. This is followed by an assessment of the likely direct economic impacts of a major New Madrid earthquake, taking into account distinctions in sectoral electricity use and resiliency in the face of disruption. The next chapter evaluates the total regional economic impacts, including multiplier effects, on Shelby County, and is followed by a chapter that extends the impact analysis to the Memphis Metro area, and the U.S. as a whole. Policy implications of these impacts are then explored, such as ways to reduce network vulnerability, to increase business resiliency, and to improve recovery. The study demonstrates that it truly does require an integrated team effort to adequately address the major issues associated with electricity lifeline disruptions in the context of natural hazards.

In addition to the unique interdisciplinary contributions of this study, it offers advances in the state-of-the-art in several of its individual disciplines. These include the refinement of the systems approach to vulnerability analysis, the mapping of census data into geographical units delineated by lifeline service areas, the integration of lifeline resiliency measures into the formal estimation of direct losses, the establishment of a methodology for estimating indirect losses that eliminates double-counting, the reformulation of the lifeline loss problem into an optimization framework, and the systematic study of how the lifelines disruptions affect emergency response organizations.

1.1 BACKGROUND

The failure and disruption of electric power systems during earthquakes can be devastating and costly. Although the costs to repair these systems have been relatively small compared to other damaged structures, such as buildings and transportation structures, the indirect impacts resulting from their failure can be far more catastrophic. For example, the inability to supply power to water distribution systems during fires has led to conflagration of large urban areas, e.g., the Oakland Fires. In addition, many businesses can fail if power is not restored in a timely manner.

Only recently have secondary effects resulting from lifeline disruption been considered seriously. Part of the reason for this slow development has been the lack of empirical data with which to validate analytical or theoretical predictions of secondary or indirect loss. Another reason for this lack of development has been that indirect loss assessment requires a multidisciplinary effort. Engineers and social scientists must work together to develop models to assess economic and social impacts. Until recently, engineers have not completely understood the measures or dimensions used by social scientists to quantify socioeconomic impact. By the same token, social scientists have not completely communicated to the engineers the importance of quantifying effects, other than direct damage, to lifelines.

As the previous discussion explains, the current effort is one of the first attempts at bringing engineers and social scientists together to focus on this important problem. Because research tasks have been defined within a larger project scope, it has been possible to link various analytic capabilities to resolve these complex issues. Although much progress has been made in this study, more work is needed to deliver a methodology and tools that can be used by utility company owners and operators in their everyday operations. In addition, only some of the potential applications of indirect loss estimation are explored in the last section of this report, which deals with policy implications.

In order to provide some perspective on where this study fits in the overall evolution of lifeline engineering, a discussion of the history of lifeline earthquake engineering in the U.S. is provided. This is followed by a discussion of important federal initiatives to improve the seismic performance of lifelines.

1.1.1 Brief History of Lifeline Earthquake Developments in the United States

> "As does a human body, a city has lifelines. In the body, they provide for the supply and the flow of energy, information and water by means of the alimentary, vascular and neurological systems. In the city they provide for the supply and the flow of people, goods, information, energy and water by means of the transportation, communication, energy and water systems.
>
> The failure to function of one of the lifelines, or its severe impairment, brings on injury or death to the human body and damage or disaster to the city. Knowledge of the risk of such failures is a stimulus for preventive measures. The acceptable level of risk is established by the individual for his body and by the citizenry for the city."
>
> — C. Martin Duke (1972)

Although the importance of lifelines to community welfare has long been understood, it was not until the 1971 San Fernando earthquake that we fully understood the extent of their vulnerabilities, particularly during natural disasters. As stated by Professor C. Martin Duke, the founder of lifeline earthquake engineering in the U.S., "the function of lifeline earthquake engineering is to provide reliable lifeline systems and components which will perform their functions in and after earthquakes and will protect property and human activity against lifeline and earthquake hazards." After the San Fernando event, it was recognized that this function had not fully been performed.

As a result of this earthquake, lifeline engineering professionals in the U.S. set a general goal to raise the state of the art internationally to the equivalent of that which prevailed for earthquake resistive buildings at that time. This goal will have been achieved "when a comprehensive set of standards of lifeline performance in earthquakes [will] have been established and have been proved out in future earthquakes." The time frame for this general goal was set at 30 years from the San Fernando earthquake.

It is now roughly 26 years after the San Fernando earthquake, and standards still are not in place for most lifelines. Although a comprehensive plan has been developed for adopting lifeline standards, it has had little momentum behind it, and as a result, many of our lifeline systems remain vulnerable to earthquake damage. In order to improve this situation, demonstration studies must be performed to illustrate the full scope of effects and impacts that may result from the failure and disruption of these systems, and the benefits that accrue from the implementation of cost-effective mitigation activities. This monograph addresses some of these issues and also helps to put into perspective the importance of considering the indirect and other broader impacts associated with the disruption of lifeline service. It is hoped that this information will be used to help achieve the goals set forth immediately after the San Fernando earthquake by those pioneers in lifeline earthquake engineering.

The following chronology summarizes some of the more important milestones in lifeline earthquake engineering and related topics in the U.S. (see also Eguchi, 1997). The major impetus to examine seismic design procedures for lifeline facilities really began with the 1971 San Fernando earthquake. Even though there had been prior earthquakes in the U.S., which had highlighted the importance of lifeline systems after major disasters (e.g., the 1906 San Francisco earthquake), the San Fernando event was the first earthquake to promulgate changes in design and construction.

Year	**Milestone**
1971	*San Fernando Earthquake (M6.4)* Significant damage to all lifeline systems. Start of long-term research program to study the effects of earthquakes on all lifeline systems (mostly National Science

Foundation funding). Many changes to lifeline seismic design and construction initiated by this event.

1974 *The Technical Council on Lifeline Earthquake Engineering (TCLEE)*

Formed to address general issues regarding the state-of-the-art and practice of lifeline earthquake engineering in the U.S. TCLEE has sponsored four major conferences on lifeline earthquake engineering; endowed the C. Martin Duke Lifeline Earthquake Engineering Award; and has published numerous monographs, design guideline documents, and special reports on lifeline earthquake engineering.

1985 *Building Seismic Safety Council (BSSC) Lifeline Workshop*

Led to an action plan for abating seismic hazards. The workshop had recommendations in four areas: public policy, legal and financial strategies; information transfer and dissemination; emergency planning; and scientific and engineering knowledge.

1986 *National Center for Earthquake Engineering Research(NCEER)*

Formed to address socioeconomic issues related to the seismic performance of lifeline systems through a multi-year grant to the State University of New York at Buffalo. This Center has brought together researchers from many different technical disciplines to focus on multi-dimensional issues (e.g., socioeconomic impacts caused by thedisruption of lifeline service).

1989 *Loma Prieta Earthquake (M7.1)*

Reaffirmed need to assess and improve seismic design and construction procedures for all lifeline facilities. Particular attention was given to the performance of highway bridge structures.

1990 *Port of Los Angeles (POLA) Seismic Workshop*

Developed a set of guidelines to be used by the port to address seismic design issues in the design and construction of new landfill areas within the port. This workshop reflected the culmination of many months of preparation and meetings among scientists, engineers and policymakers.

1990 *Public Law 101-614 (Reauthorization of the National Earthquake Hazards Reduction Program)*

Required the Director of the Federal Emergency Management Agency, in consultation with the National Institute of Standards and Technology, to submit to Congress a plan for developing and adopting seismic design and construction standards for all lifelines.

1990 *Iben Browning Prediction for a New Madrid Earthquake*

Prediction triggered many midwestern utilities to quickly anchor critical electric power equipment in the anticipation of a large New Madrid earthquake.

1991 *Lifeline Standards Workshop*

Workshop obtained comments and suggestions for revising draft plans prepared in response to Public Law 101-614, examining lifeline issues, and identified priorities for various standard development and research activities.

1991 *Workshop sponsored by the National Science Foundation and the National Communications System*

One of first workshops to focus on the effects of earthquakes on communication lifeline systems. This workshop was followed by a second meeting in 1992 to discuss different approaches to communication lifeline modeling.

1994 *Northridge Earthquake (M6.7)*

Performance of lifelines significantly improved compared to prior earthquakes in this region (e.g., 1971 San Fernando earthquake). However, concern continued over the performance of highway bridges structures.

1995 *Standardized Emergency Management Systems (SEMS)*

Required all municipal agencies in California, including lifeline operators, to develop standardized emergency response plans. This requirement was, in large part, motivated by the poor performance of water supply systems during the 1991 Oakland Hills fires in California.

1995 *G7 Bilateral Meeting between Japan and the U.S.*

Resulted in the commitment from both countries to work together to better prepare for natural disasters. This meeting has led to many U.S.-Japan research initiatives, including several that deal exclusively with lifeline performance. The 1994 Northridge and 1995 Kobe earthquakes were the key motivating factors in this development.

1995 *NIST/FEMA Lifeline Standards Development Plan*

Plan encourages the voluntary adoption of seismic design and construction standards for all public and private lifelines.

1997 *Deregulation of the Natural Gas and Electric Power Industries*

Deregulation may have multiple impacts on current and future earthquake hazard mitigation program. Increased competition leads to more utility service providers in the market, thereby lowering prices and increasing system redundancies. However, competitive pressures may limit the amount of money that a utility will spend to reduce future system vulnerabilities or to improve overall system reliability.

1.1.2 Federal and Industry Lifeline Initiatives

The federal government has historically played a major role in facilitating research and seismic evaluation programs for lifelines. With the reauthorization of the National Earthquake Hazards Reduction Program, Congress mandated that the Federal Emergency Management Agency (FEMA), in consultation with the National Institute of Standards and Technology (NIST), develop a plan for assembling and adopting national seismic design standards for all lifelines, public and private. This resulted in the formulation of the FEMA Report, *Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines*. A major feature of this plan is the recommendation that public and private partnerships be developed in order to effect implementation. As key elements of the plan, several pilot projects will be conducted to demonstrate the cost-effectiveness of various mitigation strategies. Overall, this plan will be consistent with FEMA's new initiative for an improved hazard mitigation strategy.

1.2 Overview

Chapter 2 introduces the Memphis economy in terms of its history and current structure. It also portrays the role of electricity lifelines in sustaining economic activity in all sectors. The importance of economic interdependence is made clear and serves as the basis for choosing the modeling approach of Interindustry Analysis." The core of this approach is an "Input-Output Table," a matrix of all purchases and sales among economic sectors in Memphis in a given year. The chapter concludes with an illustration of electricity lifeline "multipliers" derived from this table, which provide insight into indirect impacts of electricity disruption.

Chapter 3 provides an introduction to the Memphis electricity system as operated by the Memphis Light, Gas and Water Division (MLGW) of the City. A Geographic Information System is used to provide a two-dimensional depiction of this network, which is divided into 36 electric power service areas (EPSAs) for further analysis. The reliability of the Memphis electricity lifeline network during the occurrence of earthquakes is analyzed using Monte Carlo methods. This chapter presents the results of simulations of disruptions based on data on seismicity and data on engineering characteristics of electricity substations. The results summarize the vulnerability of the system to earthquakes ranging in magnitude of M6.5 to M7.5.

Chapter 4 provides more details of the Geographic Information System (GIS) used in the various aspects of the study. GIS imparts a spatial dimension to the Memphis economy by differentiating sectoral electricity demand in each EPSA so, in effect, the EPSAs become subregional economies. This is done by mapping U.S. Census Bureau data relating to employment by place of work onto EPSA configurations. This work would have taken weeks by conventional methods, as opposed to the expeditious approach of overlaying Census boundaries and EPSA boundaries.

Chapter 5 summarizes the results of a survey of individual business response to earthquake hazards. It indicates how vulnerable businesses in the Memphis area might be if a major earthquake were to take place. The evaluation is performed and measured in terms of building type and lifeline dependency. It also identifies the "resiliency" in the economy, which arises from various coping strategies. These include mitigation measures, such as reinforcing buildings and having backup power in place, as well as various response strategies, such as relocating business activities.

Chapter 6 discusses the various aspects of estimating the direct economic impacts of a major earthquake. The analysis combines reliability data, economic data, lifeline network, and resiliency data in each EPSA to translate earthquake-induced electricity lifeline disruptions into sectoral economic losses. The analysis translates simulation results of Chapter 3 for a scenario M7.5 earthquake into sectoral production losses in each of the EPSAs based on their employment opposition generated by the GIS results in Chapter 4. The measures of business resiliency from Chapter 5 are incorporated as well. The analysis in Chapter 6 also shows that direct production losses are not a constant factor of physical damages but depend on the timing of restoration.

Chapter 7 details the estimation of total regional impacts. Direct economic losses estimated in Chapter 6 are fed into an Input-Output table to show how lifeline disruptions ripple through the rest of the Shelby County economy. Thus, in addition to the more obvious direct effects, there are successive rounds of upstream indirect impacts on suppliers of a given business and downstream impacts on its customers. Also, the chapter provides a lead-in to policy formation. Rather than cutting back electricity usage on a proportional, or across-the-board manner, a linear programming analysis is used to indicate how economic losses can be significantly reduced by reallocating electricity across sectors and by rearranging the time pattern of recovery among substations.

Chapter 8 shows how the direct and indirect impacts estimated in Chapters 6 and 7 spread beyond Shelby County to outer rings of the Memphis metropolitan area and beyond to the United States as a whole. Moreover, a methodology is presented, based on the concept of a Social Accounting Matrix, to perform impact analyses at the census tract level. The chapter provides a broad framework for policy-making with regard to electricity lifeline and other crucial goods and services in a regional economy hit by an earthquake, including a generalization of the optimization model presented in Chapter 7.

Chapter 9 summarizes the major points of previous chapters that have policy relevance. It crystallizes several important policy implications of the analysis that can save lives, income, and jobs. The chapter also presents a policy formulation model to delineate the essence of earthquake risk problems, devise risk management solutions, identify the most effective participants to reduce earthquake risk, develop appropriate mechanisms for action, and acquire the necessary financial base and knowledge base to continue priority research and to translate it into effective policies.

2

Modeling the Memphis Economy

by Adam Rose and Philip A. Szczesniak

The city of Memphis is located in the southwest corner of the state of Tennessee on the banks of the Mississippi River. Directly to the south of the city is the state of Mississippi and across the Mississippi River to the west is the state of Arkansas. The city is spread out over 295.5 square miles of a relatively flat landscape and is classified within the five county Memphis Metropolitan Statistical Area (MSA) (3,013 square miles), which is comprised of three counties in Tennessee (Shelby County, Fayette County, and Tipton); one county in Mississippi (De Soto), and one county in Arkansas (Crittenden). The average annual temperature in the city is 62° Fahrenheit and because it is located in the middle of the "Sun Belt," Memphis averages more sunny days each year than Miami.

In 1995, the population of Memphis was 865,000. Between 1990 and 1995, the overall population grew by 27,100 or 3.2%. In 1990, the Census Bureau ranked Memphis as the 43rd most populous city in the U.S. Also in 1990, the racial make-up of the city was 55.1% white, 43.6% black, 0.9% Hispanic, and 0.4% other (U.S. Bureau of the Census, 1997).

2.1 History

Memphis was founded in 1819 by three prominent Nashvillians: General Andrew Jackson, General James Winchester, and Judge John Overton, upon land that became part of the United States in 1797. Over the next forty years the city grew by a steady influx of Africans, Germans, French, and Irish. Although its late origin averted all but damage to its natural setting from the New Madrid earthquakes of 1811-12, it suffered a human tragedy in 1838 when the native tribe of Chickasaw Indians was forced out of the city and onto the "Trail of Tears" to other parts of the United States.

By the 1860s, Memphis was the sixth-largest city in the South and became known as the "Capital of the Mid-South." This status made Memphis a focal point for Union strategies during the Civil War. However, Memphis was not well prepared for war, and thus in 1862 the city was easily overrun by the Union army. Because there was not much fighting in Memphis, the city did not endure the devastation that many other cities throughout the South suffered during the war.

Between 1860 and 1900, Memphis was primarily involved with helping to rebuild the South. During this period, Memphis began to grow as a distribution center. However, there were two setbacks to the overall growth of the city. In 1872 and 1878, yellow fever epidemics devastated the city, killing more than 5,000 people and sending nearly half of the city's population of 50,000 to seek safety elsewhere.

By the turn of the century, Memphis started showing signs that it had overcome its problems of the previous decades. Among some of the accomplishments of which the residents could boast were: 1) the first bridge erected over the Mississippi River south of St. Louis; 2) 100 miles of trolley car tracks throughout the city; 3) a web of electric lines to practically every home and business (provided by the Memphis Power and Light Company); and 4) a population of over 100,000 residents, making it the third-largest city in the South.

Between 1910 and 1950, Memphis continued to gradually grow by the guidance of E. H. Crump. He served as mayor of the city from 1910 to 1915 and remained actively involved in economic development throughout his lifetime. The Crump administration is largely credited with putting Memphis on firm financial footing (Memphis Area Chamber of Commerce, 1994).

2.2 Major Sectors of the Memphis Economy

In the second half of the twentieth century, Memphis has continued to build upon its solid heritage. For example, the city currently has one of the Nation's largest medical facilities; has become the Nation's leading distribution centers; and, due in great part to the success of Elvis Presley and the "blues" musicians on Beale Street, has become one of the Nation's premier entertainment centers.

Agriculture and related industries are a cornerstone of the Memphis economy. Although tobacco is the leading cash crop in the State of Tennessee, cotton is "king" in and around Memphis. Since Memphis is at the regional trading center for cotton farmers from Tennessee, Arkansas, Mississippi, Missouri, Kentucky, and Alabama, it is the largest spot cotton market in the world. The cotton brokerage houses alone bring in over $3 billion in gross revenues annually to the city. In addition, Memphis is a major trading center for soybeans and hardwoods. Well-known food product companies, such as Kellogg, Beatrice/Hunt-Wesson, Kraft, and Archer Daniels Midland, are all large local employers.

With respect to the construction sector, recently there have been a number of large projects in the city. Two noteworthy ones include the $62 million 20,500-seat Pyramid sports and entertainment arena and the $56 million David Taylor Naval Research Center. Other projects include a new high rise national headquarters for AutoZone and a new IRS service center comprised of five buildings that cover more than one million square feet.

In the manufacturing sector, there are over 1,000 plants found in the city. The sector was recently bolstered by an investment by Coors of $110 million for the retrofit of the former Stroh Brewing Company plant. A sampling of other recent relocations or expansions of existing businesses include Birmingham Steel Corporation, Toshiba America Information Systems, Sharp, Mazda, WESCO division of Westinghouse, International Paper, and Fisher-Price.

Memphis has made great strides towards becoming a national leader in transportation and distribution. For example, Walt Disney, Williams Sonoma, and Nike have all located major warehousing and distribution operations in Memphis. Serving these and other interests is the Memphis International Airport, which recently became the number one cargo airport in the world due in great part to being the Federal Express hub.

Memphis is also at the crossroads of several utility lifelines. These include oil pipelines, gas pipelines, and electricity transmission lines that serve not only the city, but are key to national networks. Electricity is supplied by the Memphis Light, Gas, and

Water Division of the Tennessee Valley Authority under a distributor contract.

Health care services also significantly contribute to the overall economy. Among the larger hospitals in Memphis are Baptist Memorial Hospital and St. Jude Children's Research Hospital. Baptist Memorial Hospital is the nation's largest private hospital with a staff of about 6,000. St. Jude Children's Research Hospital and the University of Tennessee-Memphis Medical School bring in more than $62 million annually in federal research funds.

Each year, many tourists come to see the many attractions in and around the city of Memphis. For example, in sports, the Liberty Bowl at the Fairgrounds has 63,000 seats. In addition, the city has been the setting for the filming of several motion pictures, most recently, "The Firm" and "The Client," both based on best-selling novels by John Grisham. Furthermore, some of the more prominent entertainers have included B. B. King, Jerry Lee Lewis, and Elvis Presley, whose Graceland Estate alone draws nearly 700,000 people each year.

The military is also a major employer in the region. The Memphis Naval Air Station at Millington employs about 12,000 people. Like many military bases across the country, the Memphis Naval Air Station has been threatened with closure. Recently, the base training command contingent has been replaced by staff from the Bureau of Naval Personnel (Memphis Area Chamber of Commerce, 1994).

Overall, the largest sectoral grouping in Memphis in 1994 was services, which accounted for 25.9% of earnings and 28.9% of employment; trade, 19.5% and 24.4%; government, 16.1% and 15.4%; transportation, 13.4% and 10.0%; and manufacturing, 12.7% and 9.1%. While earnings have increased for every sector in the economy over the period 1990 to 1994, employment has not. The government sector has accounted for the greatest loss of jobs with a decrease of 3,880. Mining has experienced the greatest percentage loss with a decrease of 21.1%. Sectors that have shown the most growth are transportation, 15.1%; services, 12.0%; agriculture, 10.8%; and retail trade, 4.4% (U.S. Bureau of Economic Analysis, 1996).

2.3 ECONOMIC INDICATORS

Since the nationwide recession in 1991, the economy of Memphis has grown at a rate above the average for the nation. Overall growth has taken place in employment, personal income, and earnings by industry. Memphis has benefited from an economic expansion that has characterized the entire Southeast since the end of the 1991 recession. Sectors that have driven this growth include transportation, agriculture, retail trade, and services (see Table 2.1).

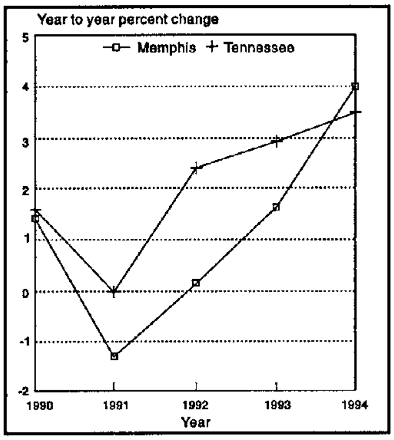
Table 2.1 Employment Percentage Growth, 1990-1994

Industry	Memphis	Tennessee
Transportation	15.1%	15.6%
Services	12.0%	18.6%
Agriculture	10.8%	-5.4%
Retail Trade	4.4%	10.7%
F.I.R.E.	0.5%	1.3%
Construction	0.1%	10.9%
Wholesale Trade	-1.3%	6.1%
Manufacturing	-2.6%	4.2%
Government	-4.3%	4.1%
Mining	-21.1%	-21.4%
Overall	4.4%	9.0%

U.S. Bureau of Economic Analysis, 1996

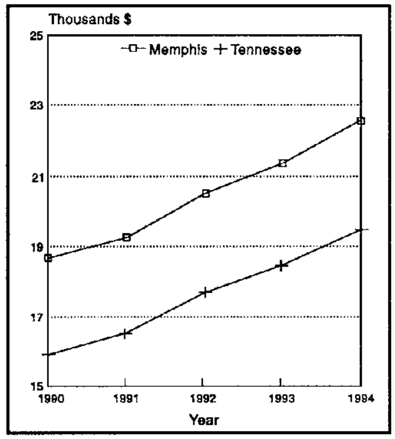
Accompanying the expansion in the economy has been an increase in employment. Between 1990 and 1994, overall employment has grown, though there was a brief setback during the 1991 recession (see Figure 2.1). While employment grew by 7,223 new jobs in 1990 in Memphis, the 1991 recession eroded that figure by 6,985. Since 1991, the economy has recovered those lost jobs and added new ones. Between 1991 and 1994, employment in Memphis grew from 530,993 to 561,605, an overall rate of 5.8%. Since that time, total employment has continued to grow, and the unemployment rate for the last quarter of 1996 was a low 4.1% (Federal Reserve Bank of Atlanta, 1997).

Between 1990 and 1994, total personal income in Memphis grew from $15,460 million to $19,375 million. This represents an increase of $3,915 million, or 25.3%. In 1994, Memphis ranked first in total personal income in the state of Tennessee, accounting for 19.2% of the total of $100,656 million. Tennessee ranked 20th in the nation and accounted for 1.8% of the national total of $5,592,000 million.



U.S. Bureau of Economic Analysis, 1996

Figure 2.1 Overall Employment Growth



U.S. Bureau of Economic Analysis, 1996

Figure 2.2 Per Capita Personal Income

Between 1990 and 1994, per capita personal income for Memphis grew from $18,674 to $22,592. This represents an increase of $3,918, or 21%. Although Memphis' total personal income ranked first in the state in 1994, its per capita personal income ranked only third. In 1994, this value was about $3,000 higher than the average of $19,450 for the entire state and about $900 higher than the national average of $21,696. Figure 2.2 shows how per capita personal income has steadily grown for both Memphis and the state ofTennessee (U.S. Bureau of EconomicAnalysis, 1996).

2.4 Economic Interdependence and Interindustry Analysis

When measuring the impact that a particular sector has on a region's economy, it is important to look beyond its direct role and to also examine the extent to which it stimulates other sectors. No economic enterprise stands alone, but rather is dependent on other businesses as suppliers or customers. These, in turn, depend on suppliers and customers of their own. The sum total of these business relations are a multiple of a given sector's direct activity, hence the term "multiplier effect." Another term, which captures these relationships, but from another perspective, is "ripple effect," which conjures up the successive waves of broader activity following an initial stimulus.

An Input-Output (I-O) table is a valuable tool that provides insights into economic interdependence. The table is composed of a set of accounts representing purchases (or inputs) and sales (or output) between all of the sectors of the economy. Official versions of these tables at the national level, prepared by the U.S. Department of Commerce, are based on an extensive collection of data from nearly all U.S. business establishments.

These accounts can serve as the foundation for more formal models, the most basic of which assume a linear relationship between inputs and the outputs they are used to produce. These structural models enable us to trace linkages between sectors and to estimate the economy-wide impacts of changes in activity in any one sector, such as electricity.

Input-Output analysis was pioneered in the 1930s by Professor Wassily Leontief. Since that time, Leontief and hundreds of other researchers have extended I-O theory, constructed tables for countries and regions around the world, and used these tables to perform a broad range of economic impact analyses. I-O analysis is considered such an important achievement that Leontief was awarded the Nobel Prize in Economics in 1973 (see Leontief, 1986; Miller and Blair, 1985; and Rose and Miernyk, 1989 for further insight into Input-Output analysis).

In addition to the official U.S. I-O table, based on U.S. Department of Commerce censuses of business establishments, tables have been constructed for many regions of the U.S., based on adjustments of national data and/or a regional sample of firms within a region. The former set of regional Input-Output tables, those based on adjusted national coefficients, has been called non-survey I-O tables, and the latter, based on expensive sampling of firms within a region, has been called survey-based I-O tables. There are five widely-used, non-survey based regional I-O tables in the United States (Brucker et al., 1987). Among them is the Impact Analysis for Planning System, or IMPLAN (1993), developed by the U.S. Forest Service in conjunction with several other government agencies including the Federal Emergency Management Agency. IMPLAN consists of national and regional economic data bases and methodologies to construct small area I-O tables and to apply them in impact studies. In this monograph, the IMPLAN I-O tables generated for the Shelby County economy, the nine-county metropolitan area, and the remainder of the U.S. were used to examine the local and wide-ranging impacts of a New Madrid earthquake.

The IMPLAN system is currently benchmarked to 1992. Given the enormous amount of data collection and reconciliation that goes into constructing an I-O model, there is typically a considerable lag between the year in which data are gathered and the date of availability of the table. The authors are satisfied that one of the best available models was utilized, and that any errors in estimating industry impacts are likely to be small.[1] Although the economy has grown, the structural relationships (ratios of input to outputs) upon which I-O models are based, have been found to be relatively stable over short time periods (3-8 years) (see Conway, 1980; Afrasiabi and Casler, 1991).

An input-output model typically determines the supply response to a given change in demand. It can also be adapted to an "allocation," or supply side, version to analyze the impacts on production of a supply shortage (see, e.g., Davis and Salkin, 1984; Oosterhaven, 1988; Rose and Allison, 1989). However, in both cases, the I-O approach represents a mechanistic response of fixed input requirements or marketing patterns. An alternative is to utilize a model that allows for a reallocation of resources in pursuit of a societable objective, such as maximizing gross regional product (GRP). In the context of lifeline disruptions associated with earthquakes, this problem could be reformulated as the reallocation of scarce electricity so as to minimize loss of GRP or employment.

A modeling framework that can perform such analyses is linear programming (LP) or mathematical (MP) in general. LP involves the maximization of an additive objective function subject to a set of linear constraints (see, e.g., Baumol, 1980; Rose and Benavides, 1997). In fact, an I-O model can be transformed into an LP format by specifying an objective function subject to the technological constraints of economic sector production structures and constraints relating to the availabilities of primary factors of production (labor, capital, and natural resources). This can be extended to include additional constraints for produced goods and services, including electricity. Such an analysis will be performed in Chapter 7.[2]

Interindustry models were chosen for this analysis because of their ability to reflect the structure of a regional economy in great detail, to trace economic interdependence by calculating indirect effects of lifeline disruptions, and to identify an optimal emergency response. The use of these models to estimate the regional impact of natural hazards dates back to the work of Cochrane (1974). Several standard input-output impact analyses of earthquakes have been performed over the past two decades (see, e.g., Wilson, 1982). More recently, several advances have been made in this approach in relation to earthquake damage in general and lifelines in particular. Kawashima and Kanoh (1990), Cole (this volume), and Gordon and Richardson (1995) have constructed multiregional I-O models to perform analyses of general earthquake impacts. Cole (1995) has also performed such an analysis at the neighborhood (census tract) level. Cochrane (1997) has recently developed an expert system using IMPLAN input-output data and a set of supply-demand balancing algorithms intended to yield ballpark impact estimates. Aspects of import adjustments in I-O models applied to estimating earthquake impacts were first suggested by Boisvert (1992).

Cochrane's (1974) original work was a linear programming formulation for the economy as a whole, as was a model outlined by Rose (1981) to minimize losses from a utility lifeline disruption by reallocating resources across sectors. Both models were simple formulations of maximizing Gross Regional Product subject to only the most rudimentary constraints—constant production technology and limits on primary factors of production. The conceptual models presented by Rose and Benavides (1997) include adjustments in I-O coefficients (including imports), consideration of excess production capacity, minimum final demand requirements for necessities, reallocation of resources over time, and the incorporation of risk (the latter in a "chance-constrained" programming formulation). A recent paper by Cole (1995) utilizes a programming extension of a social accounting matrix to examine the implications of alternative welfare criteria, including giving greater weight to certain socioeconomic or interest groups (see Chapter 8).

Of the above research, only Boisvert (1992), Cole (1995), and Rose and Benavides (1997) have explicitly examined the impacts of lifeline disruptions. This monograph advances the state-of-the-art in several ways. First, for the first time, engineering features of electric utility lifelines and their linkage to the economy are incorporated into interindustry studies. Second, neglected features of I-O impact analysis relating to the estimation of indirect effects, general input supply bottlenecks, the resiliency of production technology to electricity curtailments, and spatial (subregional) differentials in electricity use/availability are clarified. Finally, a formal optimization model is offered that incorporates the above features to examine potential policies to alter the restoration pattern of electricity utility network components across subregions, in addition to the more conventional reallocation of electricity across sectors.[3]

2.5 MEMPHIS INPUT-OUTPUT MODEL

The core of the economic model is a 21-sector input-output transactions table for Shelby County, Tennessee (the heart of the Memphis metropolitan area), which is presented inTable 2.2. The table was derived from the IMPLAN system (1993).

The I-O table contains a set of double-entry accounts. Each row represents the sales of the sector listed at the left to all other sectors, whose identities are given by the corresponding sector numbers along the top margin (column headings). Each column represents the purchases by a given sector from all other sectors in the region, as well as purchases of imports and primary factors (capital and labor listed in the value-added row), and final demand (comprised of consumption, investment, government expenditures, and exports). For example, the table indicates that in 1991 the electric utilities sector (sector 10) sold \$1.6 million and \$16.6 million, respectively, to intermediate sectors agriculture (Sector 1) and retail trade (Sector 14), as well as \$78.7 million to residential customers (personal consumption). Total gross output (sales) of electricity in Shelby County in 1991 was \$216.9 million.

The I-O table used herein is an intraregional requirements version, i.e., the entries in rows and columns 1-21 represent only those goods produced in the region that are also consumed there.

This excludes exports (which are part of final demand) and imports (presented in a lower row of the table). For the purpose of exposition, an exception was made for electricity, which is *generated* entirely outside the region by TVA.[4] To illustrate the key role of electricity, it is separated from the aggregated set of imports and included within the transactions table (intraregional commodity flows), but it is not actually part of the total regional intermediate input subtotal.

The I-O table provides insight into the general structure of Shelby County. It reflects the fact that Memphis is both a major commercial center and a major manufacturing center. Total gross output in 1991 was $66.9 billion, with the major contributors being: transportation, $4.2 billion; other nondurable manufacturing, $4.1 billion; and finance, insurance, and real estate (F.I.R.E.), $3.9 billion. The county is rather self-sufficient, with imports of $7.8 billion. In addition, a large amount of production flows out of the economy, with exports totaling $15.1 billion.

2.6 Regional Analysis of the Role of Utility Lifelines

The structure of an Input-Output table enables the "multiplier" impacts to be determined on the economy from a change in final demand in any particular sector. In Table 2.3, these multiplier effects are shown as the sum of direct, indirect, and induced effects on each sector of the Shelby County economy.[5] An example of the use of these multipliers would be to analyze the impact of a decrease in final demand for durable manufacturing goods by $100 million, which would result in a total gross output loss throughout the county economy of $182 million.

Returning to the Input-Output table, it is possible to specifically evaluate how utility lifelines (electric utilities, natural gas distribution services, and water and sanitary services) contribute directly to total gross output but also to the total multiplier effect. Table 2.4 contains the direct utility input coefficients, i.e., the amount of direct inputs needed per dollar of output. Table 2.5 contains the total (direct, indirect, and induced) inputs from public utilities for each sector.[6] For example, Table 2.4 shows that the

Table 2.2 Input-Output Table for Shelby County, TN, 1991 ($MM 1991)

Sector	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Agriculture	19.2	*	8.7	12.8	0.9	0.3	*	0.6	*	0.0	0.0	*	0.1	1.0
Mining	*	1.5	0.6	*	0.4	1.6	0.1	*	*	0.0	0.0	*	*	*
Construction	3.3	0.4	4.8	6.5	7.2	17.2	0.2	51.8	6.0	0.0	*	1.1	2.0	12.8
Food Products	0.3	*	*	266.6	4.2	1.3	*	3.1	*	0.0	0.0	*	*	39.4
Nondurable Manufacturing	6.7	0.4	11.1	163.9	291.3	88.9	2.8	34.2	1.0	0.0	0.0	3.3	5.8	35.0
Durable Manufacturing	1.9	0.3	90.4	8.4	13.6	139.9	1.5	8.8	1.6	0.0	0.0	1.7	2.7	2.8
Petroleum Refining	3.5	0.2	39.5	3.9	16.6	6.3	3.3	173.8	0.1	0.0	*	1.2	1.3	4.0
Transportation	3.2	0.2	90.3	56.7	60.4	39.4	2.0	370.1	1.9	0.0	*	2.1	4.1	17.0
Communication	0.7	0.1	12.6	33.6	17.9	20.7	0.4	71.4	7.0	0.0	0.0	0.1	6.4	28.6
Electric Utilities**	1.6	0.5	4.7	10.0	20.8	32.2	0.3	9.1	0.2	0.0	*	*	1.4	16.6
Gas Distribution	0.1	*	0.2	1.3	1.4	0.8	*	0.1	*	0.0	*	0.3	0.1	0.3
Water and Sanitary Serv.	0.4	0.1	1.2	1.3	10.2	1.6	0.1	1.3	0.3	0.0	0.0	2.5	0.1	0.6
Wholesale Trade	5.2	0.2	108.8	72.6	57.2	80.3	1.3	47.0	0.8	0.0	0.0	1.2	3.6	19.2
Retail Trade	0.9	0.1	83.4	4.1	9.7	10.7	0.1	88.3	2.1	0.0	0.0	0.3	5.8	23.3
F.I.R.E.	15.8	1.2	40.3	17.6	26.4	24.7	0.3	105.5	13.4	0.0	*	1.7	12.2	93.5
Personal Services	0.4	0.2	5.9	9.4	5.7	5.1	0.1	4.2	0.3	0.0	0.0	*	7.9	5.1
Business & Prof. Services	8.7	0.8	272.6	61.5	128.9	85.1	1.1	186.6	13.2	0.0	*	2.3	39.8	142.6
Entertainment Services	0.2	*	0.8	1.4	0.9	1.0	*	2.0	20.9	0.0	0.0	*	0.6	4.4
Health Services	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Education Services	*	*	0.0	*	0.8	1.6	*	0.1	0.1	0.0	0.0	0.0	0.0	0.4
Government	5.3	1.2	17.9	33.3	69.1	40.3	0.9	34.3	2.2	0.0	*	2.9	6.1	56.2
Errors and omissions	1.4	0.2	33.3	6.6	13.8	12.1	0.3	37.8	1.0	0.0	0.0	0.8	3.5	9.3
Total Reg. Intermed. Inputs	75.7	6.7	789.1	755.0	722.7	566.7	14.1	1,183.1	70.7	0.0	0.0	20.8	98.6	486.4
Total Imports	75.0	6.6	825.3	880.4	1,708.7	951.0	320.6	1,197.3	38.4	0.0	7.1	19.1	42.4	346.0
Total Value Added	50.5	26.2	808.3	490.0	1,635.7	1,008.9	86.9	1,775.2	345.8	0.0	3.7	12.7	1,995.7	2,069.5
Total Gross Outlays	202.6	39.7	2,456.0	2,132.0	4,080.9	2,538.7	422.0	4,193.4	455.8	0.0	10.8	53.4	2,140.1	2,911.3

Sector	15	16	17	18	19	20	21	Total Inter. Sales	Personal Consump-tion	Other Final Demand	Total Final Demand	Total Gross Output
Agriculture	11.5	0.5	1.0	1.3	0.7	1.2	1.5	61.3	14.0	127.2	141.2	202.6
Mining	*	*	*	*	*	*	0.1	4.2	*	35.5	35.5	39.7
Construction	103.2	3.1	20.7	1.4	14.1	9.5	125.7	391.1	0.0	2,064.9	2,064.9	2,456.0
Food Products	*	0.1	1.1	1.1	2.0	1.6	1.1	321.9	173.8	1,636.2	1,810.0	2,132.0
Nondurable Manufacturing	11.2	6.1	21.5	5.1	39.5	5.0	8.1	740.7	261.5	3,078.7	3,340.2	4,080.9
Durable Manufacturing	0.9	0.8	51.1	0.7	23.5	0.7	3.9	355.3	138.2	2,045.2	2,183.4	2,538.7
Petroleum Refining	1.0	0.8	6.7	0.2	2.6	0.5	6.1	271.8	98.0	52.2	150.2	422.0
Transportation	21.7	1.8	23.9	1.3	4.3	1.6	17.8	719.8	413.4	3,060.2	3,473.6	4,193.4
Communication	19.7	5.0	29.6	4.1	8.9	4.9	1.9	273.6	141.4	40.9	182.3	455.8
Electric Utilities**	1.6	3.1	5.2	0.8	3.4	0.8	13.2	125.4	78.7	12.9	91.6	216.9
Gas Distribution	*	0.1	0.3	*	0.2	0.1	3.8	8.9	1.6	0.3	1.8	10.8
Water and Sanitary Serv.	0.8	0.3	0.5	*	0.2	*	0.1	21.6	20.5	11.2	31.7	53.4
Wholesale Trade	1.9	2.9	22.8	0.5	6.3	1.8	9.7	443.4	256.2	1,440.5	1,696.8	2.140.1
Retail Trade	18.8	1.6	32.3	1.5	3.5	1.2	1.9	289.5	1,677.5	944.3	2,621.8	2,911.3
F.I.R.E.	276.0	19.4	90.8	8.4	59.1	16.6	10.9	833.9	2,073.6	1,033.1	3,106.8	3,940.6
Personal Services	4.1	3.5	22.2	0.9	2.0	0.3	0.7	77.9	254.0	309.7	563.7	641.6
Business & Prof. Services	134.3	22.0	293.8	17.4	59.5	14.1	18.5	1,503.0	625.6	836.0	1,461.6	2,964.7
Entertainment Services	1.0	0.2	2.0	14.4	0.4	0.6	0.1	50.9	134.5	15.3	149.8	200.7
Health Services	0.0	0.0	0.0	0.0	18.2	0.0	0.0	18.3	965.5	464.3	1,429.8	1,448.1
Education Services	0.1	0.0	0.1	0.0	*	*	0.7	4.8	205.4	11.8	217.2	222.0
Government	26.2	11.6	36.4	4.3	20.3	4.4	55.9	428.8	497.6	2,302.7	2,800.2	3,229.1
Errors and omissions	12.5	1.0	20.7	1.3	3.1	0.9	2.8	162.4	0.0	0.0	0.0	162.0
Total Reg. Intermed. Inputs	632.7	79.8	657.9	62.8	265.2	64.1	268.6	6,820.6	7,952.3	19,510.1	27,462.5	34,283.1
Total Imports	238.0	59.8	496.6	36.0	150.7	55.1	323.2	7,777.3	4,271.4	895.2	5,166.6	12,943.9
Total Value Added	3,057.4	501.0	1,789.5	100.7	1,029.0	102.0	2,634.5	19,523.2	0.0	0.0	0.0	19,523.2
Total Gross Outlays	3,940.6	641.6	2,964.7	200.7	1,448.1	222.0	3,229.1	34,283.5	12,223.7	20,405.3	32,629.1	66,912.2

*Less than 0.05 million.
**Electric utility sales are presented in the intraregional transactions table for purposes of exposition, but are actually imports (from TVA). Therefore, they are not counted in Total Regional Intermediate Inputs.

IMPLAN, 1993

direct inputs from the electricity sector per dollar of output of durable manufacturing is $0.0127. Table 2.5 adds indirect and induced linkages to the direct inputs. Once again, looking at the durable manufacturing sector, the total of various rounds of inputs from electric utilities is $0.0166 per dollar of output. Part of the difference of $0.0039 for this sector is accounted for by the electricity used by the direct and indirect suppliers to the manufacturing sector, such as transportation and services, while the rest is attributable to electricity purchased by households from income earned from manufacturing and its direct and indirect suppliers.

Table 2.3 Output Multipliers in Shelby County

Sector	Direct Effects	Indirect Effects	Induced Effects	Total (Multiplier)[a]
Agriculture	1.0000	0.6702	0.2292	1.8994
Mining	1.0000	0.4711	0.3159	1.7870
Construction	1.0000	0.6524	0.3177	1.9701
Food Products	1.0000	0.6295	0.2022	1.8317
Other Nondurable Manufacturing	1.0000	0.3954	0.2168	1.6122
Durable Manufacturing	1.0000	0.5248	0.2970	1.8218
Petroleum Refining	1.0000	0.0847	0.0547	1.1394
Transportation	1.0000	0.6471	0.3675	2.0145
Communication	1.0000	0.4237	0.2770	1.7007
Electric Utilities	1.0000	0.0000	0.0000	1.0000
Gas Dist. Services	1.0000	0.0845	0.1005	1.1850
Water and Sanitary Services	1.0000	0.7147	0.2824	1.9970
Wholesale Trade	1.0000	0.4701	0.5144	1.9845
Retail Trade	1.0000	0.5393	0.4061	1.9453
F.I.R.E.	1.0000	0.3601	0.1967	1.5569
Personal Services	1.0000	0.5017	0.4306	1.9322
Business, Repair, and Professional Services	1.0000	0.5909	0.3903	1.9813
Entertainment and Rec. Services	1.0000	0.6776	0.3390	2.0166
Health Services	1.0000	0.6531	0.5291	2.1822
Education Services	1.0000	0.7554	0.4851	2.2406
Government	1.0000	0.6178	0.6319	2.2496

a. The multiplier is the sum of direct, indirect, and induced effects divided by the direct effects.
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Table 2.4 Direct Utility Coefficients

Sector	Electric Utilities	Gas Distribution Services	Water and Sanitary Services
Agriculture	0.0079	0.0004	0.0019
Mining	0.0126	0.0001	0.0017
Construction	0.0019	0.0001	0.0005
Food Products	0.0047	0.0006	0.0006
Other Nondurable Manufacturing	0.0051	0.0003	0.0025
Durable Manufacturing	0.0127	0.0003	0.0006
Petroleum Refining	0.0007	0.0001	0.0002
Transportation	0.0022	0.0000	0.0003
Communication	0.0004	0.0000	0.0006
Electric Utilities	0.0000	0.0000	0.0000
Gas Dist. Services	0.0037	0.0000	0.0000
Water and Sanitary Services	0.0007	0.0048	0.0477
Wholesale Trade	0.0007	0.0000	0.0000
Retail Trade	0.0057	0.0001	0.0002
F.I.R.E.	0.0004	0.0000	0.0002
Personal Services	0.0048	0.0002	0.0004
Business, Repair, and Professional Services	0.0017	0.0001	0.0002
Entertainment and Rec. Services	0.0041	0.0001	0.0002
Health Services	0.0023	0.0001	0.0001
Education Services	0.0034	0.0003	0.0002
Government	0.0041	0.0012	0.0000
Household	0.0064	0.0001	0.0017

IMPLAN, 1993

Table 2.5 Total Utility Coefficients

Sector	Electric Utilities	Gas Distribution Services	Water and Sanitary Services
Agriculture	0.0116	0.0006	0.0028
Mining	0.0163	0.0002	0.0026
Construction	0.0060	0.0002	0.0013
Food Products	0.0081	0.0008	0.0015
Other Nondurable Manufacturing	0.0077	0.0005	0.0033
Durable Manufacturing	0.0166	0.0005	0.0015
Petroleum Refining	0.0013	0.0001	0.0003
Transportation	0.0061	0.0002	0.0012
Communication	0.0033	0.0001	0.0012
Electric Utilities	0.0000	0.0000	0.0000
Gas Dist. Services	0.0046	0.0000	0.0002
Water and Sanitary Services	0.0048	0.0052	0.0510
Wholesale Trade	0.0053	0.0002	0.0011
Retail Trade	0.0098	0.0003	0.0011
F.I.R.E.	0.0025	0.0001	0.0007
Personal Services	0.0089	0.0003	0.0014
Business, Repair, and Professional Services	0.0059	0.0003	0.0011
Entertainment and Rec. Services	0.0082	0.0003	0.0011
Health Services	0.0077	0.0003	0.0014
Education Services	0.0085	0.0005	0.0013
Government	0.0099	0.0014	0.0014
Household	0.0108	0.0003	0.0025

IMPLAN, 1993

2.7

CONCLUSION

When the New Madrid earthquakes took place in 1811-12, Memphis and its surroundings were relatively unpopulated, and the event caused little actual damage over and above the destruction of some aspects of the natural setting. The New Madrid Seismic Zone is now heavily populated, with the city of Memphis near its center. The city is an example of the advances of modern society, which makes its damage potential very high. Moreover, modern economies are characterized by high degrees of specialization, efficient location patterns, tightly wound production processes, and sophisticated human tastes. This means that the Memphis economy is, as is any major city in the industrialized world, highly interdependent and streamlined. A shock to a fundamental aspect of the system, such as an electricity lifeline, potentially affects every sector directly when it has its power source interrupted, but also indirectly when its suppliers and customers must curtail some or all of their activity as well. The streamlining of modern economies is an efficient strategy that is especially well represented in networks, but the lack of redundancy also heightens vulnerability, as the cutting of one link can bring down the entire system (not only the electricity network but the entire economy).

This chapter has introduced the major features of the Memphis economy and presented an approach referred to as *interindustry analysis*, which is especially adept at modeling economic interdependence and its repercussions. Input-output models have been widely used in natural hazard studies and are especially accessible not only to economists but planners and engineers. In the chapters to follow, some of the major contributions of this monograph are the utilization of an I-O model as a data organizing framework for economic and engineering considerations of earthquakes, the refinement of the tool to overcome some of its inappropriate applications in the past, and its extension into a mathematical programming format to examine the damage reduction possibilities of the reallocation of scarce lifeline resources.

NOTES

1. A major alternative is RIMS II (U.S. Bureau of Economic Analysis, 1997).

2. In technical terms, both I-O and LP are part of a field of economics called "activity analysis," which is the examination of production in terms of linear combinations of inputs and outputs. I-O is a simple activity analysis in which there is no choice of production alternatives (each good is produced by only a single production technique), while LP is an optimizing solution algorithm to an activity analysis problem where a choice of technique exists or when an objective function is specified. In relation to terminology, I-O is obviously an example of "interindustry" analysis, and so is LP when it is applied to the economy as a whole (as opposed to a single business enterprise).

3. This discussion of methodologies has focused on region-wide impacts, with an emphasis on the indirect. A major contribution has recently been made by West and Lenze (1994) detailing how to estimate direct regional economic losses from natural hazards by piecing together primary and secondary data; however, their study omits considerations peculiar to lifeline losses.

4. It is also the case that a small proportion of electricity (less than 5%) is generated by small independent power producers (usually involving cogeneration). These are vulnerable to earthquakes, and in some parts of the U.S. have had good earthquake safety records. They are not separately identified in this analysis, but the model framework is sufficiently general to do so if warranted for purposes of accuracy.

5. The IMPLAN multipliers we used are known as Type II multipliers. In general, a multiplier is a ratio of total impacts divided by direct impacts. Versions of multipliers differ according to the calculation of total impacts. Type I multipliers only include indirect impacts (interindustry demands) and are rarely used because they omit a major component of economic interdependence. Type II multipliers include indirect effects and induced effects (those stemming from income payments and their expenditure).

6. The total energy coefficients are derived by premultiplying the set of direct energy use coefficients by the Leontief Inverse $(I\text{-}A)^{-1}$, where the A matrix is the set of direct requirements of each input in the produc-

tion of the corresponding output (i.e., each Table 2.3 entry in rows 1-21, as well as the household income portion of the value added row divided by its column sum).

The views expressed in this paper are solely the authors' and do not necessarily reflect the views of the Bureau of Economic Analysis or the U.S. Department of Commerce.

3

Seismic Performance of Electric Power Systems

by Masanobu Shinozuka
and Howard H. M. Hwang

The most significant recent development in earthquake engineering is the recognition that traditional approaches cannot meet the growing public demand for better seismic disaster mitigation strategies to minimize human and property losses resulting from earthquakes. Traditional earthquake engineering, throughout this century, concentrated on the development of improved structural materials, and on more sophisticated methods of seismic analysis, design and construction. Obviously, further development in this direction is desirable and important, particularly in view of the significant physical damage sustained by buildings, bridges and other structures from the January 17, 1995 Hyogo-ken Nanbu (Kobe) earthquake. There are, however, a number of socioeconomic considerations that are equally, if not more important in the context of seismic disaster mitigation. These socioeconomic considerations are an integral part of the seismic hazard mitigation effort. Dealing primarily with public infrastructure systems, particularly with electric systems, the economic loss consists of direct and indirect losses. The direct loss includes the cost of repair and restoration, the loss of business revenue on the part of the owner of the system, and the economic loss suffered by the industries in the region from the direct interruption of the service by the system. The indirect loss results, in part, from the economic loss suffered by various industrial sectors not directly affected by the service interruption of the system, but whose suppliers or customers were disrupted. Indirect loss must also include the impact of human casualty in some form, though this is a matter of controversy at this time.

In this chapter, seismically induced degradation of system function is evaluated for Memphis Light, Gas and Water (MLGW) Division's electric power system. This evaluation provides the foundation for the ensuing estimation of the economic loss suffered by the regional industries in the Memphis area from the seismically induced service interruption of the electric power transmission system. In this respect, it is mentioned that the interruption of the power supply will in turn induce malfunction of the MLGW's water delivery system (Shinozuka et al., 1994) aggravating further the extent of post-earthquake human suffering and economic losses. The analytical model of the electric system used is not an exact model of the Memphis system due to the unavailability of complete information, although the model is expected to represent its approximate physical characteristics. In this regard, caution must be exercised if the numerical results are to be used for deriving specific technical and operational recommendations for the Memphis system.

3.1 ELECTRIC POWER SYSTEM

3.1.1 CONDITIONS FOR SYSTEM FAILURE

MLGW's electric power transmission network is depicted in Figure 3.1. It transmits electric power provided by the Tennessee Valley Authority (TVA) through gate stations to 45 substations in

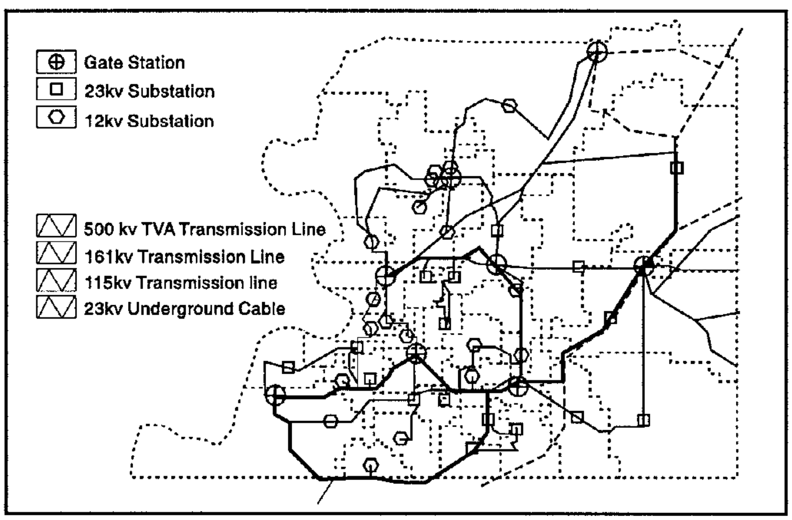


Figure 3.1 MLGW's Electric Power Transmission Network

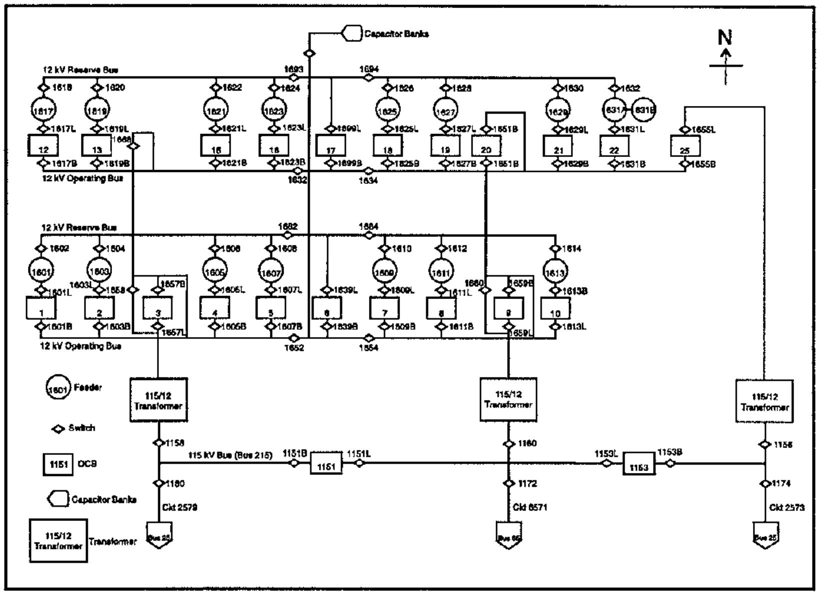
the network consisting of 500 kv, 16l kv, 115 kv and 23 kv transmission lines and gate, 23 kv and 12 kv substations. The 500 kv line and gate stations are operated by TVA, and other transmission lines and substations by MLGW. Each substation is associated with a service area, and usually one service area is served by only one substation with two exceptions.

In analyzing the functional reliability of each substation, the following modes of failure are usually taken into consideration: (1) loss of connectivity, (2) failure of substation's critical components, and (3) power imbalance. Each of these failure modes is addressed in the following subsections from the viewpoint of the ensuing reliability analysis of the MLGW's electric power transmission system.

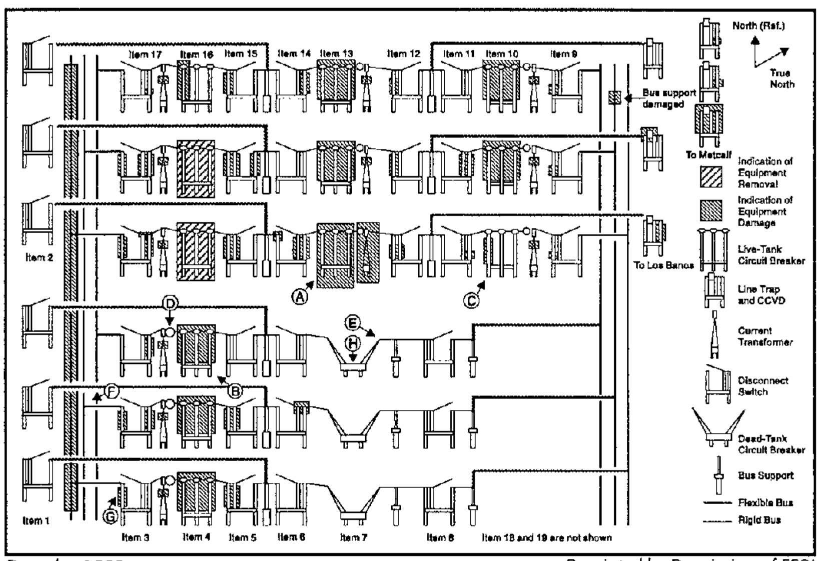
With respect to the loss of connectivity, it is noted that most of the transmission lines of the MLGW system are aerially supported by transmission towers. While by no means does this imply that the transmission lines are completely free from seismic vulnerability, it is assumed in this study that they are, primarily for the purpose of analytical simplicity. Further study on this issue, particularly on the seismic vulnerability of transmission towers, needs to be carried out.

3.1.2 Substation Model

An electric substation consists of several electric nodes subjected to various values of voltage and connected to each other through transformers to reduce the voltage and/or distribute power to the service areas. Each electric node consists of many types of electric equipment such as buses, circuit breakers, and disconnect switches. The schematic diagram of an actual MLGW substation is depicted in Figure 3.2. Among the equipment, buses, circuit breakers and disconnect switches are seismically the most vulnerable, as observed during the 1971 San Fernando, 1989 Loma Prieta and 1994 Northridge earthquakes (Benuska, 1990; Hall, 1994; Goltz, 1994). Figure 3.3 shows the damaged equipment of Moss Landing 500 kv switchyard at the Loma Prieta earthquake (Benuska, 1990). As shown in the figure, most of the live-tank circuit breakers and disconnect switches were damaged. The physical damage thus sustained by the system produced corresponding system malfunction that required concentrated repair and restora-



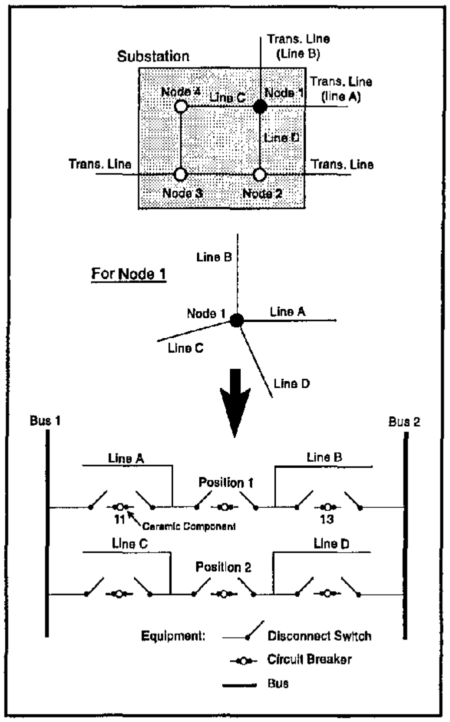
■ Figure 3.2 Schematic Diagram of MLGW Substation 21



Benuska, 1990 Reprinted by Permission of EERI

■ Figure 3.3 Damaged Equipment of Moss Landing 500kv Switchyard at the 1989 Loma Prieta Earthquake

tion effort to make them operational again. However, in spite of the damage, the system performed reasonably well during these earthquakes. Two factors played a significant role in this respect. First, the high voltage power transmission network is designed to-



Note that disconnect switches are normally closed.

Figure 3.4 Typical Node Configuration Model

pologically with a sufficient degree of redundancy in transmission circuits. Second, substations are also designed with a sufficient degree of internal redundancy. Actual equipment configuration in a node is so complicated that it defies a rigorous modeling. Therefore, a simplified but essentially accurate configuration as shown in Figure 3.4 is employed. In Figure 3.4, if only one circuit breaker CB 11 is damaged due to an earthquake, the node is still functional because all the lines remain connected to each other. However, if CB 11 and CB 13 are damaged simultaneously, Line A and Line B are disconnected from the node, thus the function of the node is impaired. Table 3.1 partially shows the line status resulting from a combination (among a possible 32) of the switch status at Position I in order to judge whether or not the corresponding mode of line connectivity still functions. In this study, it is assumed that buses and circuit breakers can be broken due to earthquake ground motion.

Table 3.1 Status Table of Position 1

Damaged Status of Switches							Line Status	
Bus 1	CB 11	Line A	CB 12	Line B	CB 13	Bus	Line A	Line B
0	0		0		0	0	0	0
0	1		1		0	0	1	0
0	1		0		1	0	1	1
0	0		1		1	0	0	1
1	0		0		0	1	1	1
0	1		1		1	0	1	1
1	1		0		0	0	0	0
1	0		1		0	0	1	0
1	0		0		1	0	1	1
1	1		1		0	0	1	0

0: Operational 1: Not Operational

Utilizing the results of the previous studies by Shinozuka et al., (1989) and Ang et al., (1992), the fragility curve $F_c(a)$ for a circuit breaker is chosen to be a log-normal distribution function with the median and coefficient of variation equal to 0.45g and 0.38, respectively. This curve is also assumed to be applicable to bus fragility for the purpose of analytical simplicity.

3.1.3 Monte Carlo Simulation

The damaged state is simulated based on Peak Ground Acceleration (PGA) values which are computed at 424 sites in Shelby County, under a scenario earthquake of moment magnitude M = 7.5 with the epicenter located at Marked Tree in Arkansas, one of the epicenters of the New Madrid Seismic Zones (see Figure 3.5). These PGA values are spatially interpolated so that they can be overlaid with the network.

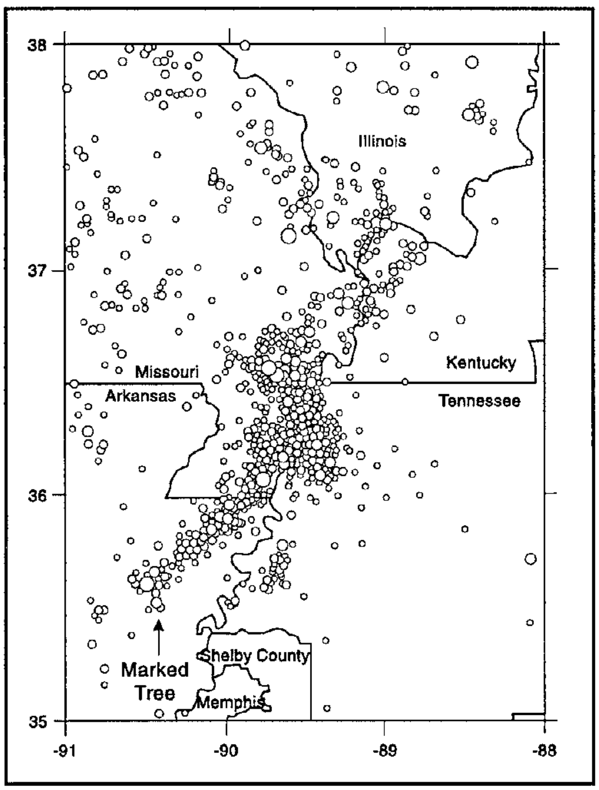


Figure 3.5 New Madrid Seismic Zone

Utilizing the Geographical Information System (GIS) capability existing at the University of Southern California (ESRI, 1988; Burrough, 1986; and Sato et al., 1991), the map of the electric transmission network is overlaid with the map of PGA identifying the PGA value associated with each substation. The fragility curve for the equipment (buses and circuit breakers) can then be used to simulate the state of equipment damage involving the equipment in all the nodes at all the substations of the transmission system. For each damage state, the connectivity and flow analyses are performed with the aid of a computer code IPFLOW developed and distributed by Electric Power Research Institute (EPRI, 1992).

Loss of connectivity occurs when the node of interest survives the corresponding PGA, but is isolated from all the generating nodes because of the malfunction of at least one of the nodes on each and every possible path between this node and any of the generating nodes. Hence, the loss of connectivity with respect to a particular node can be confirmed on each damage state by actually verifying the loss of connectivity with respect to all the paths that would otherwise establish the desired connectivity. The loss of connectivity is primarily due to the possible equipment failure not only at the node of interest but also all other nodes in the network.

As to the abnormal power flow, it is noted that the electric power transmission system is highly sensitive to the power balance and ordinarily some criteria are used to judge whether or not the node continues to function immediately after internal and external disturbances. Two kinds of criteria are employed at each node for the abnormal power flow: power imbalance and abnormal voltage. When some nodes in the network are damaged due to an earthquake, the total generating power becomes greater or less than the total demanding power. For a normal condition, the power balance between generating the demanding power is in a certain tolerance range. Actually, the total generating power must be between 1.0 and 1.05 times the total demanding power for normal operation even accounting for power transmission loss.

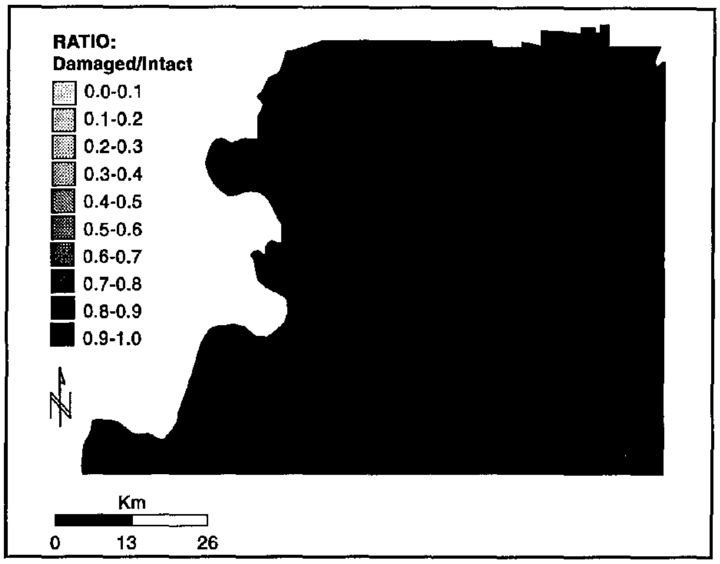
If this condition is not satisfied, the operator of the electric system must either reduce or increase the generating power to keep the balance of power. However, in some cases, supply cannot catch up with demand because the generating system is unable to respond so quickly. In this case, it is assumed that the generating power of each power plant cannot be quickly increased or reduced by more than 20% of the current generating power. When the power balance cannot be maintained even after increasing or reducing the generating power, the system will be down. This kind of outage is defined as a power imbalance. This situation, however, never materialized in this analysis.

As for the abnormal voltage, voltage magnitude at each node can be obtained by power flow analysis. Then, if the ratio of the voltage of the damaged system to the intact system is out of a tolerable range (plus/minus 20% of the voltage for the intact system), it is assumed that the node is subjected to an abnormal voltage and fails.

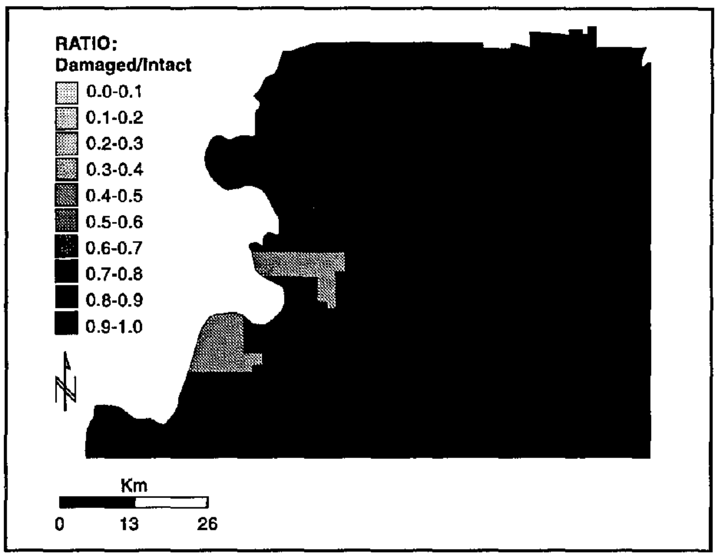
Each node which makes up a substation has a different function. Some function as a power receiving node that receives the high voltage power from the high voltage transmission line and transfer the power to the lower voltage nodes through transformers. On the other hand, some function as a power distribution node that distribute the power to the service area. In this study, if the distribution node fails or is isolated from the network, or receives an abnormal power flow, the service area is assumed to be blacked out. Appropriate modification can be made to estimate the probability of malfunction of the service area served by more than one node.

For the Monte Carlo simulation, random numbers uniformly distributed between 0 and 1 are generated for every circuit breaker and bus in all nodes. The equipment is considered to be broken, when the random number is less than the value of failure probability (fragility) for each piece of equipment under the given PGA value.

Each substation is examined with respect to its possible malfunction under these three modes of failure for each simulated damage state. In the present study, a sample of size 100 ($N = 100$) is considered for the Monte Carlo analysis. The probability P_{Em} of malfunction of a particular substation m is then estimated as $N_m/N = N_m/100$ where N_m is the number of simulated damage states in which the substation m malfunctions in at least one of the three modes. On the basis of the flow analysis performed on the network in 100 simulated damage states, the ratio of the average electric power output (real-power in MW) of the damaged network to that associated with the intact network is computed and plotted in Figures 3.6 through 3.8 under the scenario earthquake epicentered at Marked Tree with M = 6.5, 7.0 and 7.5, respec-



■ **Figure 3.6 Ratio of the Average Power Output under the Damaged Condition to the Intact Condition for Service Areas (M = 6.5)**



■ **Figure 3.7 Ratio of the Average Power Output under the Damaged Condition to the Intact Condition for Service Areas (M = 7.0)** tively. The ratio is a convenient measure to show the degradation of the system performance due to the earthquake. The average is taken over the entire sample of 100.

It is observed that the average power output still maintains almost the same level as the pre-earthquake condition for the M = 6.5 and M = 7.0 events, although the average facility failure rate at the M = 7.0 event is about four times that of the M = 6.5 event. This is considered to be the result of the redundancy effect of the electric system. However, with respect to the M = 7.5 event, the average output power falls to 50% of the level of the pre-earthquake condition, with the average facility failure rate of the M = 7.5 event also being about four times that of the M = 7.0 event. It is reasonable to conclude then that the redundancy is exhausted at this rate of facility failure.

In this study, the effect of emergency operations is not taken into account. Emergency operations are usually implemented by substation personnel in an effort to maintain the state of power balance within the criteria, taking advantage of the decline in demand. Since this operation involves human-system interaction under emergency conditions, it is difficult to construct analytical models at this time and hence its effect is not evaluated. Therefore, the actual power supply in the M = 7.5 event as shown in Figure 3.8 is probably conservative.

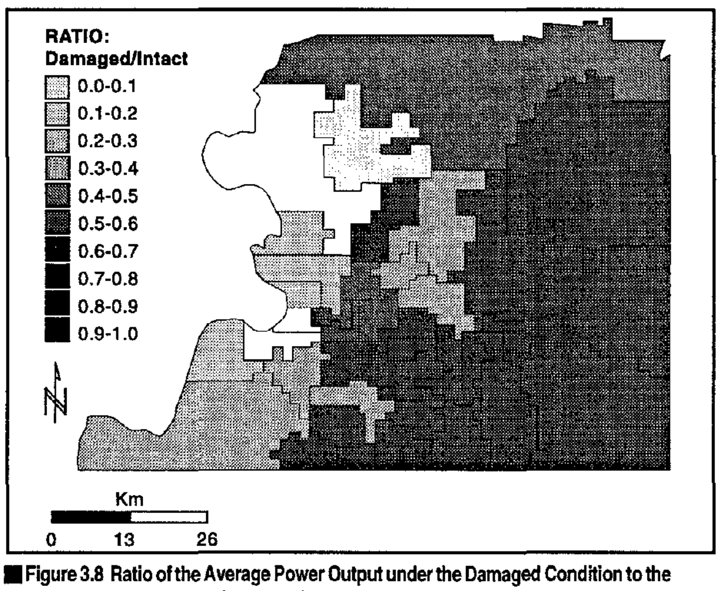


Figure 3.8 Ratio of the Average Power Output under the Damaged Condition to the Intact Condition for Service Areas (M = 7.5)

3.2 CONCLUSION

This chapter simulated the MLGW's electric power transmission system and demonstrated an analytical method by which the probability of electric power interruption for each service area can be computed. Special features of the analysis are: (1) essential use of GIS integrated with systems analysis performed on the power system; (2) the redundancy that exists in each node within a substation; and (3) the use of industry standard computer code IPFLOW for evaluation of power imbalance. These features represent significant advances in the seismic performance analysis methodology to estimate direct economic loss suffered by regional industries from the seismically induced interruption of electricity. Such direct loss estimates can also be obtained in a similar fashion for the interruption of other lifelines.

4 Spatial Analysis Techniques for Linking Physical Damage to Economic Functions

by Steven P. French

Until recently, earthquake infrastructure damage models produced results that characterized the earthquake impact in purely physical terms. For examples of these types of models, see Davis et al. (1982a and 1982b); Applied Technology Council (1985); O'Rourke and Russell (1991); and Shinozuka et al. (1992). Risk Management Software and California Universities for Research in Earthquake Engineering provide an excellent review of damage modeling techniques in NIBS, 1994. The most simplistic of these models typically characterized damage in terms of breaks per kilometer in the distribution network. More sophisticated models were developed to estimate the length of time required for service to be restored. While this type of information was an important step forward in modeling the impact of an earthquake on infrastructure systems, it was still not sufficient to understand economic impacts because there was not a clear linkage between the physical system and the economic sectors affected by service interruption of these systems.

In 1989, the National Research Council suggested that earthquake damage modeling needed to go beyond physical damage to capture the social and economic impacts of earthquakes. For the past decade, social scientists have been developing models that estimate the impact of an earthquake or other natural hazard on the social and economic functions of a city or a region. As discussed in Chapter 2, most of these models have been based on regional input-output models that define the linkages between economic sectors (see, for example, Applied Technology Council, 1991; and Rose et al., 1997.) In this project, the physical damage to the electric system serves as the input to the economic modeling. Combining the two historically independent modeling efforts promises to provide a more comprehensive and more accurate picture of the true impacts of an earthquake on a regional economy.

This type of economic modeling can help decision makers understand the full effects of an earthquake on their city or region. It can also help emergency response planners and utility operators allocate response resources in the most effective manner and set priorities for hazard mitigation programs.

This chapter describes how the spatial analysis capabilities of Geographic Information Systems (GIS) are important in modeling the economic impact of electric power system damage. Similar approaches are possible for the whole array of lifeline systems, including water, sewer, telecommunications and transportation. A Geographic Information System provides a number of features that are important to the damage modeling process. Since infrastructure systems consist of complex networks containing many components with varying degrees of fragility, the Geographic Information System's ability to store and manipulate large amounts of spatial as well as attribute information is helpful. The GIS uses a relational database to store characteristics of system components that are important in determining their response to ground shaking and other earthquake-induced effects. Unlike individual buildings, infrastructure systems are networks that are spread over wide areas that include a variety of geotechnical conditions. These differences in site conditions mean that different parts of the network are likely to experience differential ground shaking effects. It is critical to be able to associate the appropriate parts of the network with the corresponding geology and level of ground motion. The GIS provides the spatial analysis tools needed to combine site specific geotechnical information with system characteristics based on location. Most of these capabilities are well known and will not be reiterated here.

What is unique is the way in which the GIS was used to establish the linkage between economic sectors and physical damage to the electric power system. There are several ways in which the overlay or proximity functions of a GIS can be used to link economic activities or service populations to specific parts of the infrastructure system based on location. At the most elementary level, firms and employees can be associated with service areas for which changes in service can be estimated. A more refined level of analysis uses proximity analysis to associate service populations or economic activities with individual system components, such as substations or distribution lines. (For an example of this type of analysis applied to a water system, see French and Jia, 1997.) An even more precise approach would use address matching techniques to tie specific economic activities to individual systems components.

In this particular research, the first approach was selected as the most appropriate given the level of damage information available concerning the electric power system. This research utilizes the spatial aggregation techniques of the GIS to bridge the physical damage models and the economic loss models. It does so by linking small area employment information with electric power service areas. Figure 4.1 shows the conceptual approach used to link physical damage to economic impact.

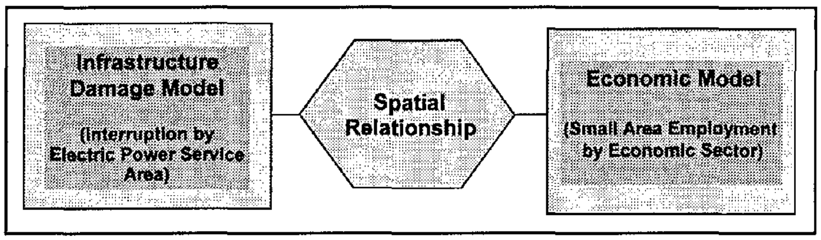


Figure 4.1 Conceptual Framework for Linking Lifeline Damage to Economic Impact

4.1 DESCRIBING THE LOCAL ECONOMY

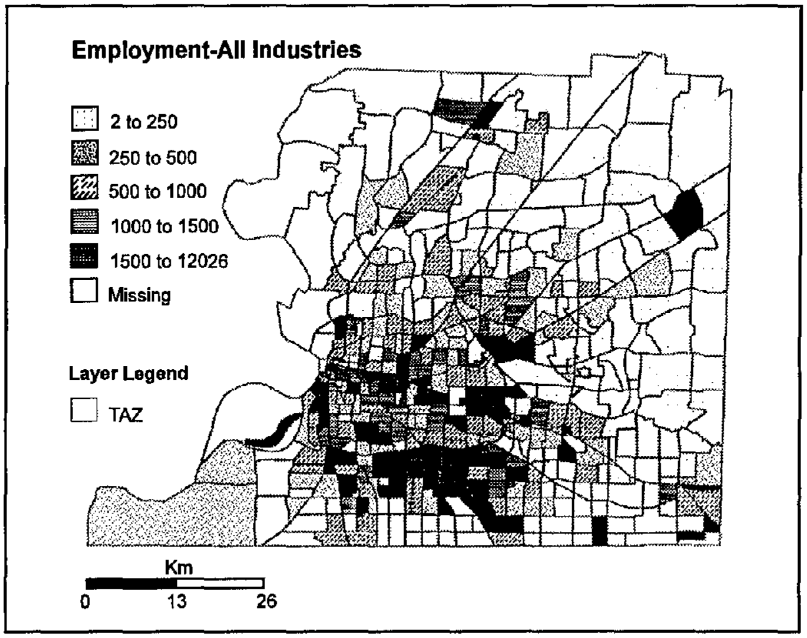
Most economic loss models characterize the size and importance of economic sectors using measures of economic output. When aggregate output measures are not available, employment is often used as a surrogate for the firm's output or production. As part of the NCEER research effort, Rose and his colleagues have developed an input-output model to estimate the interindustry impacts of damage to the electric power system operated by the Memphis Light, Gas and Water division of the City of Memphis (Rose et al., 1997). The IMPLAN input-output model contains employment in various economic sectors for Shelby County as a basis for determining the interindustry linkages in the local economy. Since the electric power lifeline model produces location specific damage information, it was necessary to find a data set that describes the sub-county location of employment in various economic sectors.

The Census Transportation Planning Package (CTPP) provides the best available inventory of employees by their work location. This data set was developed to support transportation planning through a joint effort of the Bureau of the Census and the U.S. Department of Transportation to support metropolitan transportation planning (U.S. Bureau of the Census, 1991). The CTPP data was used for Shelby County to tabulate the number of employees in each of 18 economic sectors that are compatible with the IMPLAN model. These economic sectors and their corresponding Standard Industrial Classification (SIC) codes are shown in Table 4.1.

Table 4.1 Economic Sectors

Group #	Economic Sector	Two-digit SIC
1	Agriculture, Forestry, and Fishing	01, 02, 08, 09
2	Mining	10, 12-14
3	Construction	15-17
4	Nondurable Manufacturing	20-23, 26, 27
5	Durable Manufacturing	24, 25, 28-39
6	Transportation	40-47
7	Communication/Utilities	48, 49
8	Wholesale Trade	50, 51
9	Retail Trade	52-59
10	F.I.R.E.	60-67
11	Business and Repair Services	73, 75, 76
12	Personal Services	70, 72
13	Entertainment Services	78, 79
14	Health Services	80
15	Educational Services	82
16	Other Professional Services	81, 83, 84, 86-88
17	Public Administration	91-97
18	Armed Forces	

This data set does not provide the geographic location of individual firms for privacy reasons. The location of the CTPP employment data is provided by aggregating the data to small geographic areas called Traffic Analysis Zones (TAZ's). Shelby County is divided into 618 traffic analysis zones that cover its entire area. The number of employees for each economic sector for each zone is reported in tabular form. Figure 4.2 shows the Shelby County TAZ's and the total number of employees that work in each. Similar data are available for employment within each economic sector.

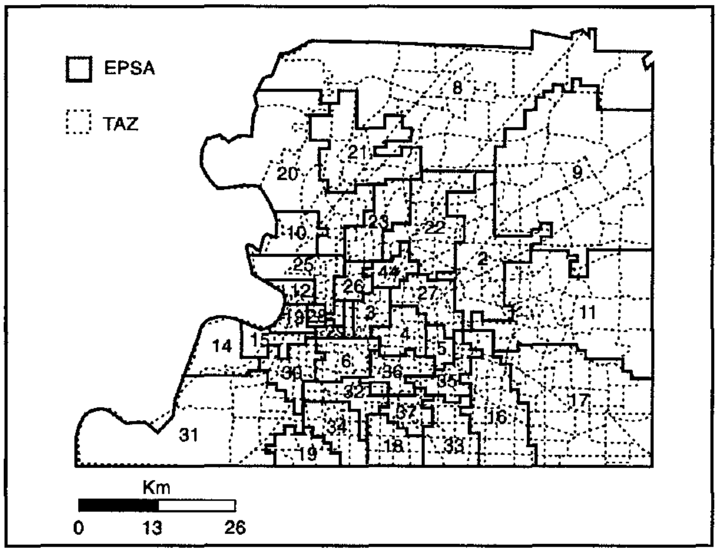


■ **Figure 4.2 Spatial Distribution of Total Employment in Shelby County by Traffic Analysis Zone**

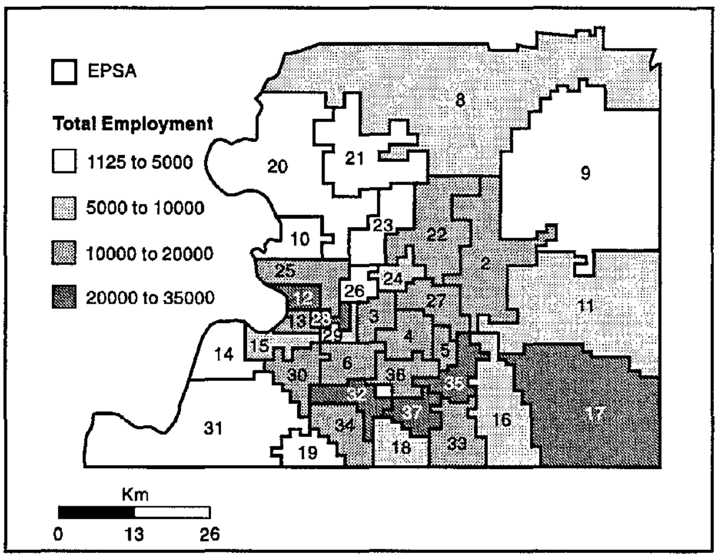
4.2 SPATIAL ANALYSIS

To make the link between the electric power damage models and the economic models, a relationship between the TAZ's and the electric power service areas was developed based on location. Several steps were required to establish this relationship: (1) 36 electric power service areas were digitized from a map provided by the Memphis Light, Gas and Water; (2) electric power service area boundaries were overlayed on the TAZ's; and (3) employment data was aggregated from the TAZ's to the larger electric power service areas. This employment by economic sector for each electric power service area was then used to estimate the direct and indirect economic impacts of power disruption caused by an earthquake.

As can be seen in Figure 4.3, each electric power service area contains between 8 and 15 TAZ's. The electric power zone boundaries are not completely congruent with the underlying TAZ



■ **Figure 4.3** Electric Power Service Areas and Traffic Analysis Zones: Memphis/Shelby County, Tennessee



■ **Figure 4.4** Total Employment by Electric Power Service Area: Memphis/Shelby County, Tennessee boundaries. For those TAZ's that are split between electric power service areas, their employment was apportioned between the two based on the area of the TAZ in each. This apportioning method assumes a uniform distribution of employment within each TAZ. Without more detailed data on firm location and more specific information of the distribution of damage over the electric distribution system, this is the best assumption that can be made and provides the best method of allocating employment to each service area. Using this method, employment in 18 economic sectors was estimated for electric power service area. Figure 4.4 shows the total employment for each electric power service zone. Similar data is available for each of the 18 economic sectors. The employment data provide the basis for estimating the economic impacts of an earthquake using the IMPLAN I-O model.

4.3 CONCLUSION

The spatial analysis techniques available in a GIS provide a mechanism for linking the formerly separate physical and economic modeling efforts using a technique known as a spatial relate. Output or employment information is generally not available for electric power service areas, thus the economic impact of the interruption of electric power could not be readily estimated. Input-output models such as IMPLAN are aspatial, so they cannot account for the spatial distribution of damage to network systems, such as the Memphis electric power system. The overlay capabilities of the GIS provide a way to create employment data for each electric power service area. Once the data are in hand, it is a relatively straightforward matter to estimate the direct and indirect economic impacts of damage to the electric system using standard input-output techniques.

This approach is applicable to a wide range of social and economic impact applications. While some of the employment data must be estimated due to the incongruence of the TAZ's and the electric power service areas, the error likely to result from this problem is certainly acceptable given the uncertainties that exist throughout the earthquake damage modeling process.

Earthquake Vulnerability and Emergency Preparedness Among Businesses

5

By Kathleen J. Tierney and
James M. Dahlhamer

To be effective, earthquake loss reduction policies must be based on an understanding of the range of impacts earthquakes produce. These impacts include not only deaths, injuries, and direct physical damage to the built environment, but also indirect impacts, including losses resulting from economic disruption. Several other chapters in this monograph have focused on how earthquake-induced electrical power service interruptions are likely to affect overall economic activity and different economic sectors in the Greater Memphis area. This chapter looks more specifically at the vulnerability of businesses in Memphis and Shelby County to physical damage and lifeline service interruption. It also explores the extent to which business owners are concerned about the earthquake problem and taking steps to avoid damage and disruption.

Despite their obvious economic and social importance, until recently there has been little systematic research focusing specifically on business vulnerability to disasters. However, several studies have documented the serious damage U.S. disasters have done to commercial districts. The downtown business district of Xenia, Ohio, for example, was devastated by a tornado in 1974. Coalinga, California virtually lost its downtown shopping area in the 1983 earthquake; in 1989, the Loma Prieta earthquake seriously damaged the downtown business districts of Santa Cruz and Watsonville. In 1992, Hurricane Andrew devastated businesses and business districts in southern Dade County, Florida.

The potential for negative economic impacts is clear in such cases. When business district damage is extensive, communities are forced to deal with a range of recovery-related problems, including potential declines in property and sales tax revenues, threats to long-term business district viability, the potential loss of important businesses, concerns that customers will go elsewhere for goods and services, and the need to undertake complex reconstruction and redevelopment projects. Disaster-related business closures can put people out of work and make it difficult for community residents to obtain the goods and services they need.

Experiencing a disaster can also have consequences for individual businesses. Disasters typically cause business interruption, either through direct damage to business properties or through the disruption of lifeline services. Being forced to shut down for even a short period of time can result in significant losses for some businesses. Businesses that are destroyed or damaged in a disaster must bear the costs associated with reconstruction; those that are forced to relocate may not be as successful in their new locations. The kinds of government grants that are made available to homeowners suffering disaster losses, such as the Federal Emergency ManagementAgency's Individual and Family Grant Program, are not available to businesses.The principal governmentally-sponsored recovery program for businesses, operated by the Small Business Administration, is a loan program, which means that businesses cannot use that form of aid without taking on additional debt.

The small but growing literature on disasters and businesses suggests that disasters may have differential effects on different types of businesses; while some may be relatively unaffected or even better off after experiencing a disaster, others may decline. Durkin's work (1984) on businesses that were affected by the 1983 Coalinga earthquake, for example, suggests that businesses that are only marginally profitable, that lease rather than own their business space, that are heavily dependent on foot traffic, and that lose expensive inventories may fare worse than other businesses in the aftermath of a disaster.

Kroll et al. (1991), in their study of the impact of the Loma Prieta earthquake on small businesses in Oakland and Santa Cruz, found that businesses in the trade and service sector were most vulnerable to disruption in that event, and that smaller firms suffered proportionately greater losses than larger ones. In contrast, some businesses, such as those involved in construction, reported being better off following the earthquake.

Alesch et al. (1993) argue that small businesses suffer disproportionately following disasters, for several reasons. They typically have lower financial reserves to draw upon, and they tend to operate in single locations, so that serious damage can put them completely out of business. Small businesses tend to be less concerned about risk management than larger businesses; they are less likely to be insured, and they have less money to invest in mitigation and preparedness.

Gordon et al. (1995), who studied the business impacts of the Northridge earthquake, found that 80% of the businesses in their sample experienced some degree of earthquake-related business interruption. They estimated that the aggregate business interruption losses incurred in that event were just under $6 billion, accounting for approximately 23% of the total dollar losses resulting from the earthquake, which they estimated at around $26.1 billion.

Other studies suggest business outcomes following disasters may be related to the access they have to certain recovery-related resources. Dahlhamer (1992), in an analysis of the loan decision-making process for 309 businesses in four Southern California communities that were affected by the Whittier Narrows earthquake, found that proprietor characteristics, business characteristics, and community location were associated with the ability to obtain Small Business Association (SBA) assistance, as well as with the loan terms offered. Dahlhamer's data indicate that the SBA uses standards similar to those of commercial lenders in making decisions about whether to grant loans and what interest rates to charge, and that certain types of businesses may be at a disadvantage in attempting to obtain SBA funds.

Several years ago, the Disaster Research Center (DRC) began carrying out research in order to shed light on business vulnerability to disasters, how disaster-related damage and disruption affect business operations, and business mitigation and preparedness practices. Following the devastating floods that struck the Midwest in 1993, DRC studied the ways in which flooding and flood-induced lifeline service interruptions affected the operations of businesses in Des Moines and Polk County, which were hard-hit by the flooding. That study found that approximately 40% of the businesses surveyed were forced to close down for at least some time during the flooding. Rates of business closure were highest for large manufacturing and construction firms and large companies offering business and professional services. Only about 20% of the businesses that closed did so because of actual physical flooding of the property. More frequently, they couldn't do business because of loss of water, electricity, sewer and waste water services, and because customers and employees lost access to the business. Compared with flood damage, the loss of critical lifeline services was a much more important cause of business closure, affecting a significantly larger number of businesses.

The floods appear to have had slight but discernable impacts, both positive and negative, on businesses in Des Moines. Approximately one year after the floods, 70% of the businesses had recovered to pre-disaster levels, 18% were better off, and 12% were worse off than just prior to the flooding. (For more detailed discussions of the Des Moines survey, see Tierney, Nigg, and Dahlhamer, 1996 and Tierney, 1997b).

A similar DRC study on businesses in Los Angeles and Santa Monica, California after the 1994 Northridge earthquake found that physical damage and lifeline service loss were widespread in the impact area. Just over half (56%) of businesses in the two study communities were directly damaged by the earthquake, 61% lost electricity, and 54% lost phone service for some period of time, although lifeline service interruption following the earthquake was less extensive and lengthy than lifeline disruption in the Midwest floods. Of the businesses surveyed, 56% closed for some period of time as a result of the earthquake. In general, small businesses were more likely to close than larger ones. The most common reasons why businesses closed were the need to clean up damage, loss of electricity, the inability of employees to come to work, loss of phone service, and damage at owners' homes that took precedence over damage at the business.

At the time the survey was conducted, approximately 18 months after the earthquake, about half of the businesses surveyed rated their well-being as comparable to what it had been before the earthquake. One-fourth of the businesses reported being better off, while for a comparable number, business had declined. Larger firms were more likely to have recovered, while businesses located in high-shaking-intensity areas and businesses that experienced operational problems following the earthquake (e.g., difficulty delivering or obtaining supplies, loss of customers) were more likely to report being worse off. (For a more detailed discussion of these findings, see Tierney, 1997a; Tierney and Dahlhamer, 1997; and Dahlhamer and Tierney, 1997; Dahlhamer and Tierney, forthcoming).

5.1 Memphis/Shelby County Business Survey

In 1993, as part of NCEER's coordinated Memphis/Shelby County seismic risk assessment project, DRC conducted a study on earthquake hazard awareness, perceived vulnerability to earthquake-induced lifeline service interruption, and disaster preparedness among proprietors of a representative sample of businesses in Memphis and Shelby County, Tennessee. In the first stage of the sampling design, the 27,197 businesses in Shelby County were aggregated by Standard Industrial Codes (SIC) into five business sectors: wholesale and retail sales; manufacturing, construction, and contracting; business and professional services; finance, insurance, and real estate (F.I.R.E.); and other businesses (agriculture, forestry, and fishing; mining; transportation, communication, and public utilities). In the second stage of the design, small (those with less than twenty employees) and large (those with twenty employees or more) businesses were randomly selected within each of the five sectors.

The survey instrument developed for the study was an 11-page mail questionnaire containing items on business characteristics; owners' perceptions of the short- and longer-term risk of earthquakes in the Memphis area; ratings on the extent to which businesses rely on various lifeline services, along with assessments of the length of time businesses could operate without those services; and questions on the extent to which businesses had undertaken mitigation and preparedness measures to contain and manage disaster-related damage and disruption.

A total of 1,840 businesses were randomly selected to participate in the study. Following a modified version of Dillman's (1978) "total design method," an initial mailing was sent to those businesses in early June, 1993. Survey participants who did not respond within three weeks were sent a reminder postcard, which was followed one month later by a second mailing of the questionnaire to non-respondents. Follow-up phone calls, timed to coincide with the second mailing, were made to businesses that had not yet replied to the survey. A total of 737 questionnaires were received, for a 40% response rate, which was adequate for undertaking the necessary statistical analyses.

Table 5.1 Business Characteristics

Median Length of Time in Business	14 Years
Individual Firm Franchise/Chain	69% 31%
Own Space Lease Space	37% 63%
Number of Employees Mean Median	 60 6

Table 5.1 contains general information on the businesses in the Memphis/Shelby County sample. At the time of the survey, the median age of the businesses was 14 years. Slightly over two-thirds were individual firms, and 63% leased, rather than owned, the business property. The study methodology was designed to target large as well as small firms, and the mean number of employees for businesses in the sample was 60. However, the median business size was six employees, indicating that the small businesses in the sample were generally very small.

This chapter discusses survey findings on business vulnerability to earthquake-induced disruption and on business mitigation and preparedness activity. To begin addressing questions of differential business vulnerability, sectoral and size differences are emphasized in the discussion.

5.2 BUSINESS VULNERABILITY

The survey attempted to assess business vulnerability to earthquake-related damage and disruption in several ways. First, to determine levels of exposure to physical damage, information on the types of buildings in which businesses of different types are located was obtained. Second, business dependency on major lifeline services and the ways in which lifeline service loss would affect business operations was assessed. Third, estimates from business owners on how long they could afford to be shut down without incurring financial losses were obtained. Finally, business owners were asked to provide their subjective ratings of the likelihood of future earthquakes and their probable consequences.

5.2.1 Building Type and Business Location

The relationship between the degree of structural damage a building sustains and post-earthquake business functionality is not linear. Obviously, if a building collapses completely or even partially in an earthquake, the businesses it houses are also likely to incur very severe damage and loss of functionality. However, the reverse is not the case: even if buildings survive an earthquake with minor or no structural damage, businesses in those structures can still suffer severe losses due to nonstructural damage, damage to contents and inventory, lifeline service interruption, or other causes. As the Des Moines case discussed above indicates, lifeline loss alone is sufficient to render businesses inoperable, even without physical damage. Thus it is difficult to make inferences about business impacts on the basis of data on building types. Nevertheless, other things being equal, businesses that are located in hazardous types of buildings, such as unreinforced masonry buildings, generally face higher risks because of the danger of building collapse and serious structural damage. This assumption seems particularly valid for Memphis, since the community has adopted no provisions for retrofitting these types of structures.

Other analyses in this monograph have focused mainly on how power system damage and subsequent service interruption will affect economic activity in the Greater Memphis region. However, since respondents in this study were asked to provide information on the type of building housing their businesses, some conclusions can be drawn about their vulnerability to structural damage. Several building types, including wood frame, brick, concrete, and steel were listed in the survey questionnaire. On the assumption that masonry buildings are most at risk for collapse and severe damage, structures were classified into two categories, "brick" and "other."

As shown in Table 5.2, 24% of the businesses in the sample reported being located in brick buildings. Small service firms (33%) were the most likely to be housed in brick structures, followed by small businesses in the F.I.R.E.(31%) and manufacturing and construction sectors (30%). While 21% of the small wholesale and retail trade businesses were housed in brick buildings, only 5% of the large businesses in this sector were located in those types of structures.

Table 5.2 Percent of Businesses in Brick Versus "Other" Buildings by Type and Size of Business (in %)

Type and Size of Business	Brick	Other
Wholesale and Retail Trade		
Small (N=141)	20.6	79.4
Large (N=38)	5.3	94.7
Manufacturing and Construction		
Small (N=67)	29.9	70.1
Large (N=30)	16.7	83.3
Business and Professional Services		
Small (N=153)	33.3	66.7
Large (N=55)	21.8	78.2
Finance, Insurance, and Real Estate		
Small (N=75)	30.7	69.3
Large (N=22)	13.6	86.4
Other		
Small (N=69)	26.1	73.9
Large (N=34)	8.8	91.2
All Businesses (N=696)	24.3	75.7

T-test results indicated that small businesses are significantly more likely to be housed in masonry structures than their larger counterparts. No significant relationships were found between economic sector and the building types in which businesses were located. Small businesses, regardless of type, are disproportionately located in buildings that have a higher probability of collapsing or sustaining severe structural damage in an earthquake.

These findings are consistent with other research indicating that a substantial proportion of the nonresidential building stock in Memphis is highly vulnerable to earthquake damage. Jones and Malik (1996), using tax assessors' records, estimate that about 12,000 of the approximately 21,800 commercial and industrial buildings in Memphis and Shelby County are masonry, and that those structures account for about 45% of the total commercial and industrial building area. This study, which focuses on businesses, rather than buildings, makes it possible to locate specific types of businesses and economic activities in particular types of structures. Although this monograph concentrates on lifeline damage and its economic impacts, physical damage to structures housing businesses will clearly be a very important source of direct and indirect economic loss in future New Madrid events.

5.2.2 Lifeline Dependency

Survey respondents were asked to rate the importance of five lifeline services — electricity, water, natural gas, sewers and wastewater treatment, and telephone services — to their ability to do business. A four-point scale, ranging from "Very important" to "Not important at all" was used.

Table 5.3 summarizes those importance assessments. A large majority of business respondents rated electrical and telephone services as very important to their operations (82% and 78%, respectively), and only a very small number rated these lifelines as unimportant. Water, wastewater treatment, and natural gas were also seen as important by Memphis businesses, but by a much less substantial margin.

Table 5.3 Importance of Utilities to Business Operations (in %)

Utility	Very Imp.	Imp.	Not Very Imp.	Not Imp. at All
Electricity	82.1	14.3	3.3	0.3
Water	27.1	33.4	31.3	8.2
Natural Gas[a]	18.4	28.7	39.5	13.4
Wastewater Treatment	22.6	31.6	32.6	13.3
Telephone	77.8	17.5	3.2	1.5

a. Asked only of businesses using natural gas.

Next, size and sectoral variations in the need for electricity and telephones (the two most critical lifeline services) were reviewed (see Table 5.4). Large businesses in the F.I.R.E. sector assigned the highest importance ratings to electricity; in fact, there

Table 5.4 Importance of Electricity by Type and Size of Business (in %)

Type and Size of Business	Very Imp.	Imp.	Not Very Imp.	Not Imp. at All
Wholesale and Retail Trade				
Small (N=148)	79.7	15.5	4.7	0.0
Large (N=41)	87.8	12.2	0.0	0.0
Manufacturing and Construction				
Small (N=71)	73.2	19.7	4.2	2.8
Large (N=29)	86.2	13.8	0.0	0.0
Business and Professional Services				
Small (N=152)	88.8	8.6	2.6	0.0
Large (N=56)	83.9	16.1	0.0	0.0
Finance, Insurance, and Real Estate				
Small (N=79)	82.3	13.9	3.8	0.0
Large (N=24)	100.0	0.0	0.0	0.0
Other				
Small (N=70)	67.1	25.7	7.1	0.0
Large (N=30)	76.7	16.7	6.7	0.0
All Businesses (N=722)	82.1	14.3	3.3	0.3

■ Table 5.5 Importance of Telephones by Type and Size of Business (in %)

Type and Size of Business	Very Imp.	Imp.	Not Very Imp.	Not Imp. at All
Wholesale and Retail Trade				
Small (N=148)	77.0	16.2	4.1	2.7
Large (N=41)	75.6	14.6	7.3	2.4
Manufacturing and Construction				
Small (N=70)	75.7	20.0	1.4	2.9
Large (N=29)	75.9	20.7	0.0	3.4
Business and Professional Services				
Small (N=152)	78.3	16.4	4.6	0.7
Large (N=56)	71.4	23.2	3.6	1.8
Finance, Insurance, and Real Estate				
Small (N=79)	83.5	16.5	0.0	0.0
Large (N=21)	75.0	20.8	4.2	0.0
Other				
Small (N=70)	80.0	18.6	1.4	0.0
Large (N=30)	90.0	10.0	0.0	0.0
All Businesses (N=721)	77.8	17.5	3.2	1.5

were no businesses in this group that did not consider electricity very important. In general, large businesses were more likely than small ones to consider electricity very important for their operations; small service-oriented businesses, 89% of which considered electricity very important, are an exception to this pattern.

Just over three-quarters of the sample judged telephone service to be very important to their business activities. This lifeline was rated as highest in importance by large businesses in the "other" category; small businesses in that category and in the F.I.R.E. sector also tended to see phones as crucial for their ability to do business (Table 5.5).

A related question in the survey asked how long firms could stay in operation if they lost any of the five lifeline services. Again, electricity was considered by respondents to be most critical for their ability to do business, with 59% reporting that loss of electrical power would cause them to shut down immediately. Telephone services were also seen as crucial for staying in business; the median length of time business owners said they could operate without phones was four hours. Owners believed they could stay open longer (about two days) without water or wastewater services and reported being least dependent on natural gas (see Table 5.6).

In other analyses using data on lifeline importance, Nigg (1995a, 1995b) found that size and sector were unrelated to reliance on electrical power; businesses universally consider this service critical.

■ **Table 5.6 Median Number of Hours Businesses Could Operate with Lifeline Loss**

Lifeline Service	Median Number of Hours
Electricity	0
Water	48
Natural Gas	120
Wastewater Treatment	48
Telephones	4

There was some variation in the assessed criticality of phone service, with small businesses in the wholesale and retail trade sector indicating they could stay open longer than other businesses if phone service were lost. Small businesses considered themselves significantly less dependent on water service than their larger counterparts, and service-oriented businesses reported greater reliance on sewer and wastewater treatment services.

These data provide a basis for ranking lifeline services in terms of their importance for continued business activity. Owners view electrical power and telephone service as crucial by both criteria discussed above—assessed importance for operations and the potential impact of service loss. Most cannot envision remaining open for any appreciable period without those services. An earthquake causing extensive damage to electrical and telephone transmission or distribution systems serving the Memphis area would thus have an immediate and substantial negative impact on economic activity.

Additionally, businesses generally cannot tolerate loss of water or wastewater treatment service for longer than about two days without being forced to close. Since restoration times for these lifelines could be lengthy following a major earthquake in the New Madrid area, their loss could also have major negative economic effects.

Data from this section of the survey were used by other NCEER investigators to quantify potential regional economic impacts of a New Madrid earthquake event. In Chapter 6, Stephanie Chang used the data to calculate measures of business lifeline dependency and resiliency for Memphis/Shelby County businesses. Those data were then combined with French's GIS-based data on employment patterns within the county's electric power service areas (see Chapter 4), data on the spatial distribution of electric lifeline service disruption, and projections on probable restoration times derived from research on recent events, to estimate the direct economic impacts of electric power disruption and restoration.

5.2.3 Perceptions of the Earthquake Threat

Table 5.7 Perceived Earthquake Probabilities (in %)

Year(s)	Very Likely	Likely	Not Very Likely	Not Likely at All
30	25.7	44.4	26.3	3.6
10	9.5	42.7	41.3	6.4
1	1.7	18.6	54.3	25.5

To assess the extent to which earthquakes were perceived as a problem within the business community, respondents were asked to rate the probability of a damaging earthquake striking the Memphis/Shelby County area within the next year, the next ten years, and the next thirty years, using a four-point scale. As Table 5.7 indicates, owners generally did not believe a damaging earthquake was likely within the coming year; although about one-fifth of the sample viewed such an event as likely or very likely, the majority rated such an event as not very likely or not likely at all. However, perceptions of the risk began to shift as longer time-frames were considered. The sample was about evenly split between respondents who thought a damaging earthquake was likely or very likely in the next ten years and those who didn't think an earthquake was probable. The proportion of those considering an earthquake likely or very likely rose further, to about 70%, for the thirty-year time window. Based on these data, it appears that business proprietors were moderately concerned about the earthquake hazard in the Memphis area. While they didn't consider the threat of a damaging earthquake immanent—i.e., something that could occur within the next year—they did assess the probability in the next one to three decades as relatively high. Subsequent analyses indicated that these risk perceptions were not related either to business size or business type.

5.3 BUSINESS PREPAREDNESS

5.3.1 ADOPTION OF PREPAREDNESS MEASURES

One of the main objectives of the survey was to assess the extent to which businesses were engaging in activities designed to reduce losses and enhance emergency response capability in the event of an earthquake. Respondents were asked to fill out a mitigation and preparedness checklist containing both general emergency preparedness and earthquake-specific items; included in the list were activities such as having the building structurally assessed, providing emergency training for employees, bracing shelves and other equipment, stockpiling first aid kits and emergency supplies, having backup power, and having a business recovery plan.

Table 5.8 summarizes owners' reports on the extent to which they had implemented these measures at their businesses. The more frequently-adopted measures were those geared toward general preparedness, rather than those that are earthquake-specific. For example, over half the businesses in the sample had obtained first aid kits or extra medical supplies (60%) and had learned first aid (51%). A moderate proportion of the businesses surveyed had stored extra office supplies (30%) and fuel or batteries (22%) for use in the event of an earthquake. A comparable percentage had purchased business interruption insurance (30%). Activities undertaken by only a small fraction of the businesses in the sample include holding earthquake training programs for employees (11%), having the business property assessed for structural safety (11%), conducting earthquake drills or exercises (9%), and making arrangements to move the business to an alternative location in the event of a damaging earthquake (9%).

Interestingly, a sizeable percentage of the sample had purchased earthquake insurance (41%) and attended meetings or received written information on earthquake preparedness (40%). These

Table 5.8 Business Preparedness Activities (in %)

Preparedness Activity	Have Done
Obtained a First Aid Kit	60
Learned First Aid	51
Purchased Earthquake Insurance	41
Attended Meetings or Received Written Information	40
Stored Office Supplies	34
Talked with Employees About What to Do in Earthquake	30
Purchased Business Interruption Insurance	30
Stored Fuel or Batteries	22
Developed a Business Emergency Plan	22
Braced Shelves and Equipment	17
Obtained an Emergency Generator	15
Stored Food or Water	14
Developed a Business Recovery Plan	13
Held Earthquake Training Programs for Employees	11
Had Engineer Assess Structural Safety of Building	11
Made Arrangements to Relocate Business in Case of an Earthquake	9
Conducted Earthquake Drills or Exercises with Employees	9

relatively high levels of information-gathering and insurance coverage can probably be explained in part by increases in earthquake awareness in the Central U.S. resulting from the 1990 Iben Browning earthquake prediction. During the late summer and fall of that year, the entire New Madrid region was bombarded with earthquake-related information; numerous organizations, including the Central U.S. Earthquake Consortium (CUSEC), the Red Cross, and the Federal Emergency Management Agency, conducted preparedness campaigns in Memphis and other Central U.S. communities. A DRC survey conducted in Memphis and Shelby County in the fall of 1990, just prior to the December 3 "prediction" date, revealed that community residents had been extensively involved in seeking and sharing information about earthquakes (Tierney, 1994). This concern evidently carried over into their business-related activities.

While the number of businesses that engaged in some of the preparedness measures asked about was relatively large, overall the business community in Memphis/Shelby County was not well-prepared for earthquakes at the time of the survey. Only two of the seventeen activities on the checklist — obtaining a first aid kit and learning first aid — had been carried out by more than half of the firms in the sample; the mean number of preparedness activities undertaken by businesses was four, and the median was three. Fifteen percent of the sample had not engaged in even one of the preparedness activities listed, and an additional 10% had engaged in only one. These data suggest that while business owners in the Memphis/Shelby County area know about the hazard and see a damaging earthquake as likely in the next 10-30 years, they are actually doing little to prepare for a future damaging earthquake.

To put things into perspective, these findings on business preparedness don't differ appreciably from what has been observed in other communities. In Southern California, where earthquake experience is much more extensive, most businesses had done little to prepare for earthquakes prior to the Northridge earthquake, and even after that event improvements in preparedness were quite small. Like their counterparts in Memphis, Southern California businesses also tended to favor the more generalized and less expensive types of preparedness activities, like stocking first aid equipment, as opposed to undertaking earthquake-specific and more costly loss reduction measures (Dahlhamer and Reshaur, 1996; Tierney and Dahlhamer, 1997).

5.3.2 Explaining Business Preparedness

To identify factors associated with business willingness to prepare for earthquakes and other disasters, several models were tested; the one discussed here expands a model developed and analyzed earlier by Dahlhamer and D'Souza (1997). Included in the model are: (1) business characteristics, specifically the age of the business, whether the business is an individual firm or a franchise or part of a chain, whether the business property is owned or leased, business size (i.e., the number of full-time employees), the financial condition of the business, as assessed by the business owner, and business sector; (2) owners' perceptions of the likelihood of a future damaging earthquake; (3) an index of owners' assessments of the importance of four lifeline services (electricity, telephones, water, and sewer and wastewater) for business operations[1]; and (4) previous disaster experience. The dependent variable in the analysis, business preparedness, consisted of an index of the 17 preparedness items listed in Table 5.8.

Regression analysis was used to test the model. As shown in Table 5.9, the overall model was significant (F=11.4901). The adjusted R^2 is .1931, indicating that the model explains approximately 19% of the variance in preparedness.

Four of the model variables were significantly related to business disaster preparedness. Size was by far the strongest predictor of preparedness levels; larger businesses were significantly more likely to engage in preparedness activities than their smaller counterparts. This is consistent with previous research on business disaster preparedness (Drabek, 1991, 1994a, 1994b; Quarantelli et al., 1979). Size may be indicative of business financial well-being[2], or may make it more likely that a firm will have resources to support preparedness activity. Conversely, smaller firms may simply lack the resources or staff to devote to preparedness activities. Mileti et. al., (1993), for example, note that large firms are more likely to have staff who are specifically assigned disaster preparedness tasks.

Owners of business properties were significantly more likely than lessees to undertake loss reduction measures. This finding is consistent with research on households, which indicates that homeowners are better prepared than renters (Turner, Nigg, and Paz, 1986). Compared to those who lease, building owners may see themselves as having more to lose in the event of a disaster. Owners may also have access to more financial resources than renters for undertaking preparedness activities. Finally, they may be able to undertake to a wider range of preparedness activities; for example, they can have an engineer structurally assess the building housing the business, while renters would be highly unlikely to do so.

Business type is also significantly related to preparedness. Businesses in the F.I.R.E. sector were significantly more likely to engage

Table 5.9 Regression Coefficients and Standard Errors for Business Preparedness Model

Independent Variables	Standard Errors	Unstandardized Coefficients	Standardized Coefficients
Business Characteristics			
Age of Business	.0768	.0901	.0504
Individual Firm or Franchise	.3202	-.3716	-.0486
Own or Lease	.3059	1.0763	.1486[b]
Number of Full-Time Employees	.1106	.5400	.2265[b]
Financial Condition	.1826	.1898	.0433
Wholesale/Retail	.4274	-.4129	-.0537
Manufacturing/Construction	.5167	-.2121	-.0206
Business/Professional Services	.4533	.3309	.0432
Finance/Insurance/Real Estate	.5377	1.6370	.1508[a]
Risk Perception			
Likelihood of an Earthquake	.3421	1.5364	.1803[b]
Utility Importance			
Utility Importance	.0762	.1472	.0816
Disaster Experience			
Previous Disaster Experience	.4465	.7721	.0701
R^2			.2115
Adjusted R^2			.1931
F-Value			11.4901[b]

a. $p \leq .01$ b. $p \leq .001$

in preparedness activities than other businesses. Although this survey can't directly shed light on why is the case, it is possible that outreach efforts have targeted this sector more than others. For example, the Central United States Earthquake Consortium (CUSEC) has paid considerable attention to potential earthquake impacts on the F.I.R.E. sector. Some other investigators have also found sectoral differences in preparedness levels (see, for example, Drabek, 1991, 1995; Mileti et al., 1993).

Finally, risk perception, or owners' estimates of the likelihood of a future damaging earthquake, was also significantly related to preparedness. Those who saw the likelihood of a future damaging earthquake as high were significantly more likely to engage in preparedness activities than those who were less concerned about the earthquake problem.

The variables in the model that were unrelated to business preparedness included the age of the business, owners' ratings of the importance of utilities for business operations, the company's status as an individual firm or a franchise, owners' assessments of the financial condition of the business, and previous disaster experience. The finding regarding disaster experience is surprising, since other studies (e.g., Drabek 1994a, 1994b; Mileti, et al., 1993) have found that businesses that have gone through one or more disasters are more likely to prepare.

5.4 CONCLUSION

Memphis businesses are clearly vulnerable to earthquake-induced disruption; this vulnerability stems in part from the types of buildings in which they are housed and from their dependence on lifeline services that are susceptible to earthquake damage. Nearly one-fourth of the businesses surveyed are located in masonry buildings; this pattern alone suggests high levels of exposure to potential earthquake damage. Business operations are critically dependent on electrical power; more than half the businesses in the survey indicated that they would be forced to shut down immediately if they were to lose electricity. Telephone service is also viewed as extremely important by Memphis firms; the loss of this service would also be felt immediately by business operators. Although services such as water and wastewater treatment are considered somewhat less important, the loss of those services would have a detrimental impact within a relatively short period of time—approximately 48 hours. A major New Madrid earthquake has the potential for causing extensive lifeline service disruption in the Memphis area. The survey data indicate that such disruption would almost immediately result in significant business interruption losses.

Business owners in the Memphis area are aware of the earthquake problem, and while they do not see the threat of a damaging earthquake as immanent, they do consider the potential for such an event over the next three decades to be significant. This moderately high level of concern is attributable in part to the heightened public curiosity and large-scale public awareness and education campaigns that resulted from the 1990 Iben Browning New Madrid prediction scare. The data also show that awareness of the earthquake problem is important for explaining actions taken with respect to the hazard. Belief in the probability of a future damaging earthquake is high among those who are willing to engage in preparedness activities. However, consistent with the disaster literature, hazard awareness alone wasn't sufficient to explain preparedness.

Despite moderately high risk perceptions, Memphis businesses generally have not been enthusiastic about adopting hazard mitigation and preparedness measures. While some businesses show a slight inclination to prepare by taking one or two minimal steps, such as keeping first aid supplies on hand or having employees learn first aid, they are highly unlikely to engage in more comprehensive preparedness efforts.

The survey data also point to factors that are associated both with earthquake vulnerability and with levels of preparedness among Memphis businesses. Business size is one such factor. Small businesses are more likely than their larger counterparts to be located in masonry buildings, the kinds of structures that are particularly vulnerable to major earthquake damage. At the same time, small businesses are less likely than large ones to undertake preparedness activities. Survey findings regarding the importance of size are consistent with other research, as well as with DRC's recent study on the Northridge earthquake (Tierney, 1997a), which suggest that small businesses were especially vulnerable to disaster-related losses and disruption in that event. Sector also turned out to be important for preparedness in Memphis; firms in the F.I.R.E. sector were most likely to have taken steps to prepare for earthquakes and other disasters. Owners of business properties were more likely to adopt preparedness measures than renters, indicating that building ownership creates additional incentives for loss reduction.

Finally, the Memphis data suggest that the commonly-used approach to encouraging earthquake and general disaster preparedness among businesses, which emphasizes public awareness and education but stops short of using stronger incentives, is achieving little. Lack of awareness is not the main barrier to hazard reduction. The Memphis survey respondents knew about the region's earthquake problem, but for most business owners that awareness did not translate into action. To encourage broader adoption of loss reduction measures, such measures must be made attractive to and affordable for the business community. Businesses must also understand that their economic survival may well hinge on the extent to which they are able to cope with disasters and their impacts. Recognizing this need, the Central U. S. Earthquake Consortium, the Tennessee Valley Authority, and other groups have been actively supporting the work of the Memphis Business Emergency Preparedness Council (BEPC), a private-sector organization whose objective is to address the physical and economic vulnerability of Memphis area businesses to earthquakes and other disasters (CUSEC, 1997). Organizations like BEPC have an important role to play, since the evidence from Memphis and other communities shows that currently businesses are far from sold on the need for reducing disaster losses.

NOTES

1. Assessments of the importance of natural gas were not included in the index since only one-third of the businesses in the sample reported using this lifeline service.

2. Financial soundness alone is not sufficient to stimulate preparedness, however; in the current model, business financial condition was found to be unrelated to preparedness levels.

6

Direct Economic Impacts

BY STEPHANIE E. CHANG

This chapter focuses on the estimation of the direct economic impacts that result when earthquake-related lifeline service disruption impedes normal economic activity. First, an overview of concepts, current methodologies, and issues is provided. A new methodology, developed as part of the NCEER coordinated study of the seismic vulnerability of lifelines in the Memphis area, is then presented. The crux of this methodology involves a synthesis of engineering assessment of lifeline network reliability (Chapter 3) with socioeconomic analysis of lifeline usage (Chapter 5) and urban development patterns (Chapters 2, 4, 7 and 8). Estimation of direct impacts associated with electricity disruption is presented as a case study. The conclusion discusses the significance of the methodological developments, potential applications, and areas for further research.

6.1 Scope of Direct Economic Impacts

The definition of direct versus indirect economic impacts presents a common source of confusion, as the terms have unfortunately been used in different ways by different researchers. Furthermore, the definitions also depend to some degree on the context of the problem, in particular, whether the context is the impact of lifeline disruption, buildings damage, or total losses due to an earthquake. For present purposes, the basic concept used by Boisvert (1992) and Cochrane (in NRC, 1992) is applied.

> Direct losses include losses of plant and equipment which stem directly from the physical damage plus any associated

loss of employment. The indirect losses in GRP result from the multiplier or ripple effect throughout the economy due to supply bottlenecks and reduced demand as a result of the direct losses. (Boisvert, p.223)

This concept is also utilized in the standardized loss methodology currently being developed for the National Institute of Building Sciences (NIBS) (RMS, 1997). The definition suggests that direct losses are those which occur as an immediate consequence of physical damage at the site of production. The implication is that direct economic losses are suffered by the users of this damaged plant or equipment, while indirect losses are suffered by others as a result of reduced economic transactions.

In the case of lifelines, the application of this concept requires some clarification because lifelines provide essential services to many sectors of the economy and generally consist of networks that service many sites of production. Consider an example where an earthquake causes damage to several electric power substations. This causes a blackout to several parts of a city and forces the temporary suspension of various business activities. Technically, the user of the damaged *facilities* (i.e., the substations) is the electric utility company itself, which clearly suffers some direct economic losses. Ambiguity arises, however, because the users of the electricity *service* (i.e., the customers) in the blackout areas can also be said to have suffered direct economic losses as a result of the electricity disruption at the site of production. Their business interruption losses do not result from "multiplier" or "ripple" effects. This is illustrated by continuing the example, whereby business interruption in the blackout areas reduces production of a certain good. Businesses in the unaffected areas which require this good in their production process are forced to reduce their activities as a result of this supply bottleneck (assuming they are unable to import a substitute within a short period of time). These latter businesses thus suffer indirect losses resulting from direct losses incurred in the blackout areas.

In the present context of earthquake-induced lifeline damage, direct economic losses are therefore considered to include production losses in various economic sectors attributable to electricity outage at their production site. It should be noted that this definition differs from that used in some other studies, including most notably the Applied Technology Council (1991) report ATC-25, *Seismic Vulnerability and Impact of Disruption on Lifelines in the Conterminous United States.* In ATC-25, "direct" losses are confined to repair costs. Business interruption losses imposed on lifeline users are defined as "indirect" economic losses. Losses due to reverberations of "indirect" losses throughout the economy are considered "secondary" losses. ATC-25's "direct" and "indirect" losses are both considered to be "direct" losses under the definition used in this study, while ATC-25's "secondary" losses are defined as "indirect" impacts here.

A further point of clarification is required with regard to impacts on sectors other than private businesses. While it is true that households and governments will also suffer property damage and attendant losses in a natural disaster, these losses are not evaluated in the current approach to direct loss estimation. This approach is based on the need to avoid double-counting losses, as emphasized by Cochrane:

> ... the level of economic activity can be measured by counting expenditures, or incomes, but not both. Income ... must be equivalent to value of the products produced. This is because the price of a product reflects all the costs incurred in its creation, which in this case is the sum of wages, interest, and profits. This simple result provides an important loss-accounting guide: damage assessments should focus on incomes lost or spending lost, but not both. Either should yield the same result. (NRC, p.101)

Since losses to household income can also be counted as reductions in wages paid from business production, they should not be counted *in addition* to business interruption losses. Similarly, losses to government revenue include reduced corporate and personal income taxes and should not be counted in addition to business interruption losses.

Finally, a clarification is required regarding the distinction between direct damage and direct economic losses. Direct damage includes repair costs or, alternatively, the replacement value of damaged plant and equipment. These are losses to a region's capital *stock* or assets. Direct economic losses derive from lost production (or equivalently, lost income) resulting from this physical damage. These constitute reductions in the region's *flow* of income or Gross Regional Product (GRP). This chapter focuses on the estimation of direct economic losses, rather than direct damage.

6.2 Current Estimation Methodologies

The economic impact of earthquakes and other natural disasters has been gaining attention in recent years, and many methodological improvements have been made with respect to estimating the direct and indirect regional economic losses beyond the costs of repairing physical damage. However, only a few studies have specifically addressed lifeline disruption impact. Furthermore, most of these studies have focused on estimating indirect, rather than direct, economic impacts. For example, studies such as Boisvert, 1992; Gordon and Richardson, 1992; Rose and Benavides, 1993 and the NIBS project (RMS, 1997) do not actually provide a methodology for estimating direct economic losses associated with lifeline disruption. Such a methodology therefore remains an important missing link in the complete loss estimation procedure.

ATC-25 constitutes perhaps the principal reference for estimating direct economic impacts of lifeline disruption in earthquake disasters. The ATC-25 methodology assumes a simple proportional relationship between the extent of lifeline service disruption and the extent of ensuing production losses. Specifically, for a particular lifeline i and industry j, ATC-25 provides an "importance factor" I_{ij} . This importance factor is based on expert judgment and derives from data in another reference report by the Applied Technology Council (1985), *ATC-13: Earthquake Damage Evaluation Data for California*. These importance factors indicate the percent of production that would be lost if lifeline service were *completely* disrupted. For example, an importance factor of 0.75 would indicate that in the event of complete utility service disruption, 75% of normal production would be lost due to reduced productive capacity. ATC-25 further assumes that the first 5% of utility service interruption can be absorbed without loss, presumably due to excess capacity, substitution possibilities, or other forms of resiliency. Going from 5 to 100% lifeline service disruption, losses decrease proportionally from 0% to the maximum indicated by the importance factor.

The importance factors reflect the extent to which different industries are dependent upon different lifelines. It is not necessarily the case that 100% disruption of a particular lifeline leads to 100% loss of economic output because a particular industry may depend upon the lifeline only to a limited degree. Thus the average value of the importance factor for electricity across all sectors is 0.86, while the average for natural gas is 0.32. This indicates that industries are generally much more dependent upon electricity than upon natural gas. For the electricity lifeline alone, the importance factor ranges from 0.30 for the transportation and warehousing industry to 1.00 for industries such as petroleum refining. The economic impact of earthquake-induced lifeline service disruption in an urban area may therefore vary significantly depending upon the particular industry and lifeline under consideration.

In addition to ATC-25, other studies have also provided methodologies for estimating direct economic losses from lifeline disruption. For example, Eguchi et al., 1992 focused on evaluating energy systems, specifically natural gas, electricity, and petroleum. Using data from the Department of Energy, the study estimated energy usage factors indicating dependency on different energy sources for various states in the Midwestern U.S. For a scenario earthquake in the New Madrid Seismic Zone, restoration time factors are calculated based on ATC-13. Economic losses from energy service disruption for each industry in a state are calculated by combining the lifeline restoration factors with the energy use factors. Industry losses are combined by weighting them with their share of the regional economy (in terms of value added), and results are summed across states in the affected area to obtain the total direct economic loss (which are referred to in that study as "indirect" losses). Thus unlike ATC-25, Eguchi et al., 1992 does not rely upon importance factors determined by expert judgment. In addition, the spatial dimension of lifeline disruption and restoration is explicitly recognized insofar as geographic subareas (i.e., states) comprising the impacted region are analyzed separately. However, the estimation procedure is an approximate one intended to produce order-of-magnitude rather than accurate results.

6.3

CONCEPTUAL FRAMEWORK

This chapter presents a general methodology for evaluating the direct economic losses caused by seismically-induced disruption of lifeline service in an urban area. The ATC-25 methodology and issues identified in Eguchi et al., 1992 provide a basis for the conceptual framework. However, several improvements or refinements are developed. In particular, emphasis is placed on utilization of empirical data for the specific study area and evaluation of loss distribution within a geographic information system (GIS) context. An earlier version of this methodology was presented in Chang et al., 1995.

The basic premise of the improvements and refinements is that direct economic losses will depend very much upon specific local engineering and socioeconomic conditions. First, as shown in Chapter 3 on system performance, the disruption to lifeline service caused by an earthquake is likely to be uneven across the impacted area. Furthermore, as seen in Chapter 4 on GIS representation, the distribution of pre-earthquake economic activity is also uneven across the impacted area. The pattern of concentration will also differ from industry to industry. Thus the physical extent of lifeline service disruption region-wide will vary across industries. Furthermore, the economic impact of this service disruption will be determined by how dependent a particular industry is on that lifeline. To take into account all of these factors, the methodology consists of four steps: (1) development of a lifeline usage or dependency model on an industry basis, (2) estimation of the spatial distribution of economic activity throughout the urban area, (3) estimation of lifeline service restoration, and (4) assessment of direct losses through evaluation of the spatial coincidence of economic activity with lifeline service disruption over time.

6.4 CASE STUDY: ELECTRICITY DISRUPTION IN NMSZ EARTHQUAKE

The direct economic impact methodology is developed here in the context of the Memphis/Shelby County case study. However, the methodology is general and applicable to other lifelines and other seismically vulnerable regions of the country.

6.4.1 BUSINESS RESILIENCY TO LIFELINE DISRUPTION

A simple lifeline usage model is developed based on the ATC-25 methodology. However, three improvements are made: first, rather than applying expert-based "importance" factors that are meant to reflect conditions in California, these factors are empirically calibrated with data from the study region. This data derives from the NCEER study of business vulnerability in Shelby County conducted by researchers at the Disaster Research Center (DRC) at the University of Delaware (see Chapter 5). In addition, the time element is explicitly recognized to take into account the recovery timepath after the disaster. By incorporating the time element, alternative recovery strategies can be addressed in terms of their potential for reducing total economic loss. Finally, the spatial dimension of lifeline service disruption and economic impact is considered through use of GIS information. This not only addresses an important source of differential impact between industries but also allows for more sophisticated analysis of the economic implications of alternative recovery strategies.

Based on ATC-25, a simple usage-based loss model is proposed as follows:

$$l_{ijt}^{s} = \frac{(1-r_{ijt})}{0.95} \cdot (d_{it}^{s} - 0.05) \quad \text{if} \quad d_{it}^{s} > 0.05 \qquad (6.1)$$

$$= 0 \qquad \text{if} \quad d_{it}^{s} \leq 0.05$$

where $l_{ijt}^s (0 \le l_{ijt}^s \le 1)$ is the direct economic loss from lifeline i disruption for industry j in service area s in time period t after the disaster, $r_{ijt} (0 \le r_{ijt} \le 1)$ is a "resiliency" factor, and $d_{it}^s (0 \le d_{it}^s \le 1)$ is the percent of lifeline service disruption. Economic loss is expressed relative to normal economic production levels. As in ATC-25, it is assumed that the first 5% of lifeline service disruption can be absorbed without economic loss. Alternatively, without this 5% assumption, the loss model can be written as:

$$l_{ijt}^s = (1 - r_{ijt}) \cdot d_{it}^s \qquad (6.2)$$

As in ATC-25, it is assumed that economic loss increases in proportion to extent of lifeline service disruption up to some maximum. In ATC-25, the "importance" factor I indicated the maximum percent of production loss that would be associated with complete lifeline disruption. Here, a "resiliency" factor r is defined as the percent of remaining production in the event of complete lifeline outage, or equivalently, one minus I. This resiliency factor is specific to lifeline i and industry j and reflects lifeline usage characteristics and dependency.

Resiliency factors are calibrated from results of the DRC survey of businesses in Shelby County. Specifically, businesses were asked, "How long could your business operate without electricity?" and similarly for other lifelines. The responses were classified according to major industry. For each industry, a cumulative distribution of temporary business closures was inferred according to the duration of lifeline disruption by week. It was assumed that output is uniform across establishments in an industry, so that the closure of x percent of businesses at any time represents a production loss of x percent in that industry. The percent of business closures at a given point in time can then be assumed to represent $1 - r_{ijt}$, the percent loss of output in that industry due to complete lifeline disruption.

Table 6.1 compares these survey-based resiliency factors with the expert-based estimates provided in ATC-25 for electricity. These factors represent an average over the first month after the disaster and are presented for nine major industries comprising the private sector of the economy. Factors from the two sources are generally consistent. In some industries (notably agriculture, mining, construction and TCU) the differences are quite great; however, as these do not represent major sectors of the Memphis economy, the differences are not a source of great concern. Similar comparisons for water and natural gas lifelines can be found in Chang et al., 1995. In general, the factors differ quite significantly in the case of these other lifelines. As with electric power, where significant differences occur, in general the expert-based estimates overestimate resiliency — and hence underestimate impact — as compared with the empirical data.

Table 6.1 Resiliency Factors for Electricity by Industry

Industry	ATC-25	Survey-based
Agriculture	0.50	0.15
Mining	0.10	0.33
Construction	0.60	0.17
Manufacturing	0.02	0.04
T.C.U. [a]	0.45	0.15
Wholesale Trade	0.10	0.06
Retail Trade	0.10	0.08
F.I.R.E. [b]	0.10	0.07
Services	0.16	0.07

a. Transportation, Communications, and Utilities
b. Finance, Insurance, and Real Estate

The similarities and differences may be partly explained by variations in lifeline usage across regions of the country. In particular, natural gas usage and dependency is probably greater in the Midwest than in California. Electricity dependency, on the other hand, is generally very high in any region of the country. In addition, the types of businesses comprising a particular industry may vary interregionally. There is also the possibility that expert judgment on lifeline dependency does not coincide very closely with the opinions of business operators. It should be kept in mind that while business operators may have a better sense of lifeline dependency in Shelby County, their opinions probably do not reflect actual earthquake experience.

According to the survey-based factors in Table 6.1, the manufacturing industry is the most dependent upon electricity in the sense of having the least resiliency to electricity outage. Wholesale and retail trade, FIRE and the services industries are also highly dependent upon electricity. Mining would appear to be the least dependent industry; however, as the resiliency factor was estimated from a very small sample (three businesses), this calibration may not be very reliable.

It should be noted that the resiliency factors are considered independently for each lifeline and do not account for other earthquake impacts such as damage to buildings and other structures. It would be incorrect to sum losses from Equation 6.1 for electricity, water, and natural gas without accounting for some redundancy in their impacts. However, in the current study, only electricity is evaluated.

In contrast to ATC-25, the current methodology models changes in the resiliency factor over time. That is, as lifeline service disruption is sustained over a period of weeks, some of the initial resiliency "cushion" would be gradually worn away. Stored energy reserves, as an example, may be depleted. On the other hand, it is also possible that in the course of the recovery process, resiliency may increase due, for example, to businesses setting up new temporary electric generators. In general, however, the resiliency factor is expected to decrease over time. This is schematically illustrated in Figure 6.1. The y-intercept of the solid line, r_0, indicates the resiliency factor immediately after the disaster; one week later, resiliency decreases to r_1.

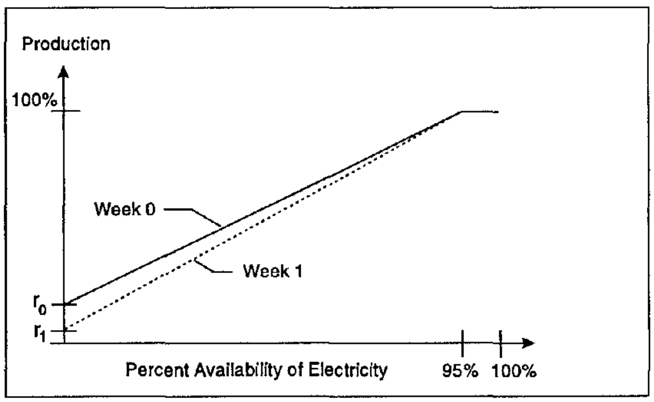


Figure 6.1 Impact of Electricity Disruption on Production

To summarize, the resiliency factor r_{ijt} serves to modify the impact of lifeline service disruption. If it is assumed that the first 5% of disruption cannot be absorbed without loss, then a resiliency factor of 0 indicates that industry *j* has no flexibility in dealing with lifeline (e.g., electricity) loss; for example, 70% disruption in electricity would lead to 70% loss in production. A resiliency factor of 0.1 would mean that 70% disruption of electricity would lead to 63% loss in production. Over the course of the repair and restoration period, in a particular service area *s*, both the disruption factor *d* and the resiliency factor *r* are expected to decrease. These produce opposite effects, so that the net impact on the loss factor *l* in Equations 6.1 and 6.2 may be either an increase or decrease at any point in time.

6.4.2 Location of Economic Activity

For a given lifeline such as electricity, the loss model represented by Equation 6.1 (or alternatively 6.2) indicates the direct economic impact for a particular industry *j* in a particular service area *s*. Total direct economic impact depends upon the locational distribution of economic activity among all service areas in the impacted region. At time *t*, the total direct economic impact for industry *j* can be evaluated as a weighted sum over all service areas:

$$L_{jt} = \sum_s l_{ijt}^s w_j^s \qquad (6.3)$$

$$\text{where } w_j^s = \frac{X_j^s}{X_j}$$

$L_{jt} (0 \leq L_{jt} \leq 1)$ is the percent loss of production in industry *j*, l_{ijt}^s is the loss factor defined in equation 6.1 (or 6.2), *X* represents output, and the area weights w_j^s are indicated by the share of industry *j* production accounted for by area *s*. Total direct economic loss for the impacted region in dollar terms (ΔX_t) is then:

$$\Delta X_t = \sum_j L_{jt} \cdot X_j \qquad (6.4)$$

where X_j is the normal production level for industry *j*.

In the current application, this estimation of total direct economic impact requires information on the distribution of pre-earthquake economic activity among Shelby County's electric power service areas (EPSAs) for each industry. Analysis described in Chapter 4 (GIS Analysis) produced results in terms of pre-earthquake employment in different industries by EPSA. For convenience, it can be assumed that there is uniform labor productivity within each industry so that each employee accounts for the same amount of output. With this assumption, the GIS database on employment can also be interpreted as a representation of output distributed across EPSAs in the county for each industry and can be utilized directly for inferring the weights in Equation 6.3.

Note that Equation 6.4 assumes that there is no inter-area product substitution following the earthquake. In an actual disaster, to some extent, producers in less heavily impacted EPSAs could "make up for" losses in more heavily impacted areas, for instance by making use of excess capacity or working overtime. The extent to which this is possible will depend upon a number of factors, including length of power disruption, concentration of businesses in the industry, specialization of businesses in each area, extent of building and other lifeline damage, and condition of the local transportation network. For example, retail trade stores for clothing are spread throughout the impacted area and losses in one EPSA could be made up for by additional sales in another. On the other hand, specialized manufacturing businesses making a particular machine tool have little potential for inter-area product substitution. While such substitutions are very difficult to take into account, their potential suggests that the loss results from the following analysis can be considered an upper bound estimate.

6.4.3 Lifeline Service Disruption and Restoration

The model also requires information on the disruption of electric power in various service areas over time. For the scenario earthquake considered in this study, information on initial service disruption is available from the reliability analysis in Chapter 3. However, lifeline performance is only evaluated for the immediate post-earthquake situation. Further assessment will be needed to estimate recovery timepaths across the affected area.

The restoration of electric power is modeled on the basis of three main assumptions deriving from experience in past earthquakes. First, restoration proceeds from areas of least to areas of heaviest damage. This assumption is based on observations from disasters such as the Northridge and Great Hanshin (Kobe) earthquakes (LADWP, 1994; Chang and Taylor, 1995). Second, restoration proceeds nonlinearly, with most customers having power restored quickly and proportionally fewer customers being restored as time elapses. The restoration curve can be approximated with the following functional form:

$$R = 1 - e^{-bct} \qquad (6.5)$$

where R is the percentage of customers with power restored, e is the base of the natural logarithm, t is a time index, and b and c are constants. Based on data from the 1994 Northridge earthquake (LADPW, 1994), b is estimated to be 2.75, where t is measured in days. In this base case, c is taken to be 1. Third, it is assumed that the restoration curve in Equation 6.5 can be scaled to other disasters through the parameter c. This scaling is based on the estimated time to complete restoration of the system. In the Northridge earthquake, restoration was essentially completed in four days; in the much more devastating Memphis scenario, a rough approximation of fifteen weeks was used based on results from ATC-25. In other words, it is assumed that post-earthquake restoration of electricity service proceeds according to a general pattern or restoration curve that can be described by Equation 6.5. While the shape of the restoration curve is assumed to be consistent across earthquake events, the actual restoration timeframe may vary.

Restoration times in the various electric power service areas (EPSAs) can then be inferred. The restoration of service across the county can be modeled as a step function approximating Equation 6.5, where each step represents restoration of service to an individual EPSA. This is illustrated in Figure 6.2. The order in which EPSAs are represented in this step function is determined by the degree of initial damage, since it is assumed that service is restored sequentially from areas of least to greatest damage. The "height" of each step represents the share of customers that can be found in the associated EPSA. The share of customers can be approximated by the proportion of jobs the area contains. The "width" of each step is determined by the shape of the overall restoration curve. In Figure 6.2, for hypothetical service areas 1 to 4 ordered from least to heaviest damage, shares of

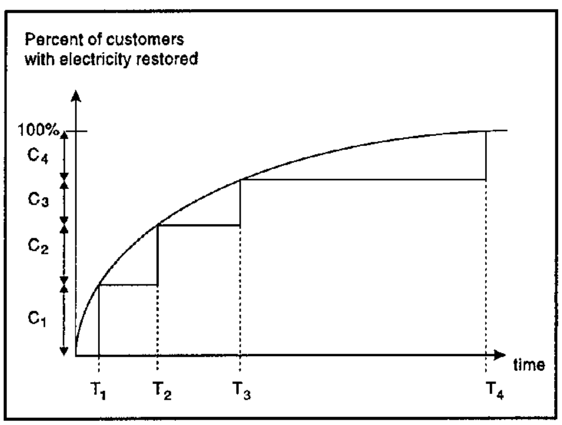


Figure 6.2 Schematic Diagram of Restoration Curve

the total number of customers with electricity disrupted are respectively C_1 through C_4. Based on the restoration curve for the county, the restoration times for each service area are respectively t_1 through t_4.

In the Memphis study, results from the reliability analysis in Chapter 3 were used to group the EPSAs into "impact zones" according to the degree of initial damage, as indicated by the reported average ratio of available electric power. These groups, ranging from 1 (least damage) to 6 (greatest damage), are shown in Table 6.2.

Table 6.2 Characteristics of Impact Zones

Zone	Elec. Availability "Ratio"	Number of EPSAs	Percent of Employment	Restoration Timeframe
1	0.5 - 1.0	17	55.9%	1 week
2	0.4 - 0.5	6	13.8%	2 weeks
3	0.3 - 0.4	5	10.7%	2 weeks
4	0.2 - 0.3	3	2.9%	2 weeks
5	0.1 - 0.2	4	14.1%	5 weeks
6	0.0 - 0.1	1	2.5%	15 weeks

It should be noted that to be consistent with the reliability analysis, electricity disruption is assumed to derive from failure of equipment at transmission substations. Compared to other components of electric power systems such as power lines and distribution substations, these are the most time-consuming to repair after an earthquake and are therefore typically a controlling factor in the restoration of the entire system. For this reason, the functionality of transmission substations can be used to represent the availability of electric power in a given area.

6.4.4 Deterministic vs. Probabilistic Analysis

The methodology described up to this point is a deterministic one. In other words, it pertains to the evaluation of a scenario of lifeline service disruption. However, the methodology can be readily extended to accommodate a probabilistic approach. This can be achieved through developing a direct linkage with the reliability analysis described in Chapter 3. In particular, the reliability results include estimates of average post-earthquake availability of electricity by electric power service area. These estimates are based upon Monte Carlo simulation analysis, in which the particular earthquake event is repeatedly simulated to produce a series of lifeline disruption realizations. Each of these simulations evaluates the probability of malfunction of nodes within a particular transmission substation serving that EPSA and the ensuing reduction in electric power levels. Each Monte Carlo realization can be interpreted as a "scenario" whose impact can be evaluated according to the direct economic loss methodology outlined above. In other words, each of the Monte Carlo simulations can be carried through to the point of evaluating the economic impact of lifeline disruption. The series of simulations can then be combined to yield a probabilistic estimate of economic loss.

In the application developed here, a hybrid rather than fully probabilistic approach was used for ease of exposition. To reduce the number of calculations required, the average disruption over the 100 Monte Carlo simulation cases was applied directly to estimate the associated average direct economic loss in the initial period. This is mathematically equivalent to estimating direct economic losses for each of the Monte Carlo simulation realizations and taking the average over these losses. The equivalence derives from the linear relationships assumed in the model and can be verified with a simple numerical example.

However, this equivalence holds only in the initial time period after the disaster, before any restoration has been completed. The restoration model described above suggests that the restoration timepath for a particular EPSA would differ between the simulation cases because of variations in both the absolute amount of electric service disruption and the relative severity of this disruption as compared with other EPSAs. In this sense, the restoration timepath estimated for the "average" case does not represent restoration in any one of the actual simulations.

However, utilization of the average electricity availability figures rather than each of the underlying simulation results individually can be justified on several grounds. First, the primary purpose of this study was to develop and demonstrate a methodology for estimating direct losses. In addition, the direct economic loss results should be compatible with the methodology for estimating the associated *indirect* economic losses. Estimating indirect losses for each of the 100 Monte Carlo simulations would have involved an excessive amount of effort and resources, as can be appreciated from reviewing the following chapter. Furthermore, the loss-minimizing optimization methodology developed as part of the indirect loss estimation project is best applied within a deterministic or case-study context rather than in probabilistic terms.

The preceding discussion suggests that the results of this study should be interpreted rather carefully. Because the analysis is not fully probabilistic, the resulting estimates of direct economic impacts should not be interpreted as expected values of direct losses in a literal sense. On the other hand, because the results do not correspond to any one lifeline disruption scenario or even to an average over several scenarios (taking into account the restoration timepath effect), they are not strictly deterministic outcomes, either. This difficulty can be resolved by keeping in mind that the purpose of this exercise is to demonstrate a methodology. In this context, the resulting estimates of direct loss can be *considered* as deterministic outcomes of a particular scenario. The same would apply to results from the indirect loss estimation.

The meaning of the direct economic loss estimates clearly depends upon the interpretation of the systems reliability results and the assumptions made above. For example, in the present case study, the reliability results indicate a probabilistic average of the percent of electric service disruption in a given service area. In other cases, reliability analysis may indicate the probability of either having or not having service. That is, there may be no intermediate damage states corresponding to partial lifeline service availability. In this case, the loss factor would be

$$l_{ijt}^{s} = P_t^s(d_i) \cdot r_{jt} + (1 - P_t^s(d_i)) \qquad (6.6)$$

where $P_t^s(d_i)$ is the probability of lifeline i disruption in area s at time t and r is the resiliency factor defined earlier. If the recovery timepath were assumed to be the same across all areas, for example,

$$P_t^s(d_i) = P_0^s(d_i) \cdot (1 - \frac{t}{T}) \qquad (6.7)$$

where $P_0^s(d_i)$ is the initial probability of disruption and T is the amount of time to full recovery, then the associated direct economic loss estimates would represent expected values of economic loss in a probabilistic sense.

6.4.5 RESULTS

Results for the Memphis case study are presented here for the methodology described in Equations 6.1 and 6.3. As an illustration, the pre- and post-earthquake production patterns for the manufacturing industry are shown in Figure 6.3. Production in each EPSA is shown relative to the pre-earthquake County total. The comparison clearly demonstrates the effect of lifeline disruption patterns throughout the county. Recall that electricity disruption was most severe in the northwestern quadrant of the county.

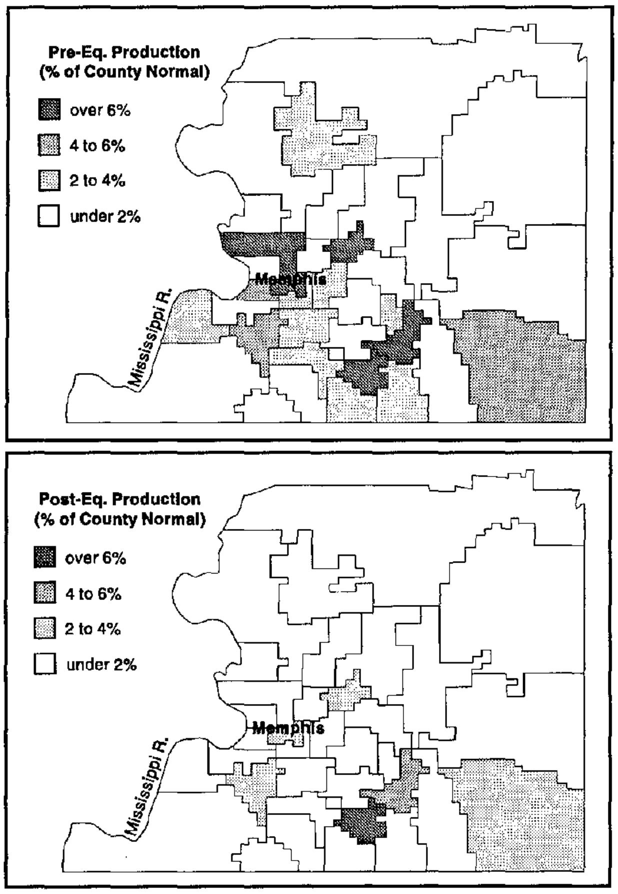


Figure 6.3 Pre- and Post-Earthquake Production, Manufacturing Industry

Table 6.3 shows the estimated post-earthquake production levels at selected weeks after the earthquake. Post-earthquake production is shown as a percent of normal output. Recall that full restoration of electricity service was assumed to require fifteen weeks, based on results in ATC-25. To facilitate comparison across different sectors of the economy, results are presented for the standard nine-industry classification that corresponds to one-digit Standard Industrial Classification (SIC) codes.

■ Table 6.3 Post-Earthquake Production by Industry and Week After Disaster (in %)

Week	Agr.	Min.	Con.	Mfg.	T.C.U.	Whs.	Ret.	F.I.R.E.	Svc.	Total
0	62	80	61	49	61	53	53	51	50	53
1	77	69	73	66	72	70	73	69	66	69
2	96	89	93	89	95	96	96	87	91	92
5	99	100	99	98	100	100	100	100	100	99
14	99	100	99	98	100	100	100	100	100	99

Initial direct impact is quite severe across all industries in the economy. Initial losses (week 0) range from a low of 20% in the mining industry to 51% in the manufacturing industry. Most industries, however, initially suffer a 40-50% loss in production due to electricity disruption. However, with the assumed restoration pattern shown in Table 6.2, recovery proceeds more rapidly for some industries than for others. The mining industry, for example, recovers only 9% of production in the first two weeks after the disaster while the services industry recovers 41%. Overall, considering both the degree and duration of impact, the manufacturing and services industries suffer the greatest losses.

Results of the direct loss estimation procedure described above can be applied to assess the indirect losses as described in the following chapter. Note, however, that the actual direct loss estimates used in that chapter differ slightly from those presented in Table 6.3. This is because the latter use loss factors from Equation 6.1 while the former use factors from Equation 6.2.

6.5 CONCLUSION

This chapter has presented a methodology for assessing direct economic losses caused by lifeline disruption in earthquake disasters. This methodology synthesizes results from engineering systems reliability analysis and socioeconomic investigation that were presented in previous chapters. The results consist of estimates of reduced post-earthquake levels of economic production in major industries over the course of the immediate impact and recovery periods. These results can be applied directly in the indirect loss estimation methodology described in the following chapter.

As illustrated in the case study application to Memphis, this methodology provides several significant advances over existing loss assessment techniques. First, it extends direct loss estimation to consider both the temporal and spatial dimensions of the loss and recovery process. For example, in addition to evaluating the immediate total impact on an affected region, the methodology considers how this impact is distributed across different areas within the region. Thus it is able to take advantage of systems engineering analysis that indicates how lifeline service disruption varies across the impacted region. In addition, it considers how the economic impact is reduced over the course of the recovery process, specifically in relation to a likely pattern of service restoration. Furthermore, economic impact is evaluated according to both the extent of lifeline service disruption and its duration. Differences between industries or sectors are considered in terms of their lifeline usage patterns and their resiliency to lifeline disruption.

Consideration of temporal, spatial, and sectoral dimensions of impact is important for several reasons. First, it improves the accuracy of the methodology and the reliability of the results. This also has benefits for estimating the associated indirect losses. Second, it provides a means for taking into account various dimensions of local economic conditions. In the Memphis case study, for example, local information was used to calibrate business resiliency to lifeline disruption, as well as the distribution of economic activity at risk throughout Shelby County. Third, these dimensions serve to establish the link between systems engineering analysis and macroeconomic analysis. Finally, by incorporating these dimensions, the loss estimation methodology can evaluate an extended set of policy tools for application to loss reduction. These include both post-disaster recovery strategies and pre-disaster planning, such as the prioritization of lifeline network restoration and mitigation.

In addition, the methodology developed here provides a basis for evaluating economic impact within a probabilistic rather than a deterministic framework. Existing methodologies evaluate economic impact in deterministic terms. The discussion in this chapter establishes a preliminary method for utilizing engineering reliability results to analyze the associated economic losses in probabilistic terms. (For reasons presented earlier, however, a hybrid rather than fully probabilistic approach was actually implemented in the Memphis case study.) A probability-based approach can potentially be important for quantifying the uncertainty associated with estimates of economic loss.

In view of the preceding discussion, several important areas for further research can be identified. The direct economic loss methodology should be improved with more refined models and further empirical calibration. In particular, the accuracy of the proportional impact assumption in the loss factor model (Equations 6.1 and 6.2) should be examined. The models should also be tested against actual earthquake experiences such as Northridge and Kobe. In addition, the development of a probabilistic framework for estimating economic losses should be explored further. Particular attention should be paid to quantifying the uncertainty associated with the loss estimates. Sensitivity analysis could also be very useful for identifying both a range of probable losses and the most influential factors determining impact. Further applications of the methodology can be developed for other types of lifelines, other regions, and other natural disaster events. Another particularly important area for further research consists of the interaction between impacts from different types of lifeline disruption (e.g, evaluating losses when both electricity and water are unavailable), as well as between impacts from lifeline disruption and structural damage. GIS technology may be very useful in facilitating analysis of these interactions. Finally, attention should be paid to developing the methodology as a loss reduction tool for informing pre-disaster mitigation and post-disaster recovery decisions.

7

Regional Economic Impacts

by Adam Rose and Juan Benavides

The purpose of this chapter is to present and apply a methodology for evaluating the economic impact of a catastrophic earthquake on the Memphis economy, with special reference to indirect losses stemming from a disruption of electricity services. Electricity is one of several utilities termed "lifelines" because of their crucial role in maintaining social and economic systems and because of their network characteristics, which make them especially vulnerable to disruption from natural disasters. Although losses from earthquakes are often measured in terms of property damage resulting from the actual ground shaking, the emphasis in this chapter is on the subsequent loss of production of goods and services by businesses directly cut off from electricity service and by businesses indirectly affected because their suppliers or customers are without power.

This chapter builds on the work of several researchers whose results have been presented in previous chapters. This includes the input-output table representation of the Memphis economy presented in Chapter 2, the electricity lifeline vulnerability analysis of Chapter 3, the GIS mapping of sectoral employment into Electric Power Service Areas in Chapter 4, the analysis of business resiliency in Chapter 5, and the estimates of direct lifeline disruption losses in Chapter 6. Subsequent chapters will build on this analysis, to help further demonstrate the capabilities and potential of a multidisciplinary effort to understand key aspects of earthquake events and to improve society's ability to cope with them.

In Section 7.1, a methodology is presented to estimate total regional economic losses when electricity lifeline services are cut back proportionately across all users as a result of a 7.5 M earthquake in the New Madrid Seismic Zone. A methodology to estimate the optimal reallocation of scarce electricity resources is presented in Section 7.2. A base case simulation indicates the potential production loss over a 15-week recovery period could amount to as much as 7% of Gross Regional Product. Reallocation of scarce electricity across sectors could reduce the impacts by almost 70%. Additionally, an improved restoration pattern of electricity transmission substations across subareas could reduce losses by more than 80%.

The analytical framework used to perform this analysis is *interindustry economics,* which includes input-output analysis, social accounting matrices, and linear programming (see also Chapter 2). These methods are able to show how the loss of production in one sector transmits itself to other sectors through a series of *multiplier* effects. The state-of-the-art of these tools is advanced by showing how information on business preparedness and resiliency can be incorporated into a basic input-output framework. A further advance is to show how a linear programming extension of input-output analysis can be used to evaluate alternative policies for rationing scarce lifeline resources. Although the attention of the study is confined to the Memphis area, these methodological contributions are readily generalizable to other contexts.[1]

7.1 Estimation of Total Regional Impacts

7.1.1 Input-Output Impact Analysis

Indirect impacts can be estimated from the direct effects presented in the previous chapter by using input-output impact analysis. Assuming no resiliency adjustments for the moment, electricity lifeline disruptions due to earthquakes can be translated into potential output reductions in each sector as follows:

$$\Delta X_j = \sum_s \sum_j d_e^s w_j^s \overline{X}_j \qquad (7.1)$$

where

$j(j = 1,...,21)$: economic sectors
$s(s = 1,...,36)$: electricity service areas

X_j: gross output of sector j for the entire region

d_e^s: loss factor for electricity disruption by service area s, $0 \le d_{et}^s \le 1$

w_j^s: fraction of sector j output produced in region s, $\sum_s w_j^s = 1$

$\overline{X}_j^s$: gross output of sector j in area s before the earthquake

However, for inclusion into an input-output model, the gross output changes must be converted into final demand changes because the latter are the conduits through which external shocks are transmitted. A decrease in electricity availability, d_e, translates into a change in final demand sector, ΔY_j, as follows:

$$\Delta Y_j = (I - A_i)\Delta X = (I - A_i) d_e w^s \overline{X} \quad (i{=}1,\ldots,21);(s{=}1,\ldots,36) \quad (7.2)$$

where the symbols represent entire vectors (all sectors) and where A_i is a row vector of A, the matrix of technical coefficients, a_{ij}, representing the value of direct input i needed to produce one dollar of output j.[2]

Then, the standard I-O impact formula was utilized to determine total output impacts: $\Delta X = (I - A)^{-1}\Delta Y$. Had the original vector of ΔX_j's been used in place of the ΔY_j's on the right-hand side of the standard I-O impact equation, an electricity demand level reduction larger than the disruption level caused by the earthquake would have been obtained (the percentage difference being equivalent to the weighted average of the sectoral multipliers). This would mean that the available electricity would be underutilized in the region, a nonsensical outcome for earthquake disruptions of more than a few days, where firms have time to modify their supplier and customer linkages so as to utilize all available resources. Thus, there may be *no* indirect effects of the utility lifeline disruption over and above the initial estimate of electricity curtailments in each sector and the corresponding gross output reductions. What may appear to be indirect effects are essentially part of the simultaneous direct impacts of electricity disruptions in all industries. "Indirect" effects are artificially created, for computational purposes, because measured impacts are scaled back into final demand effects (which are *not* equivalent to direct impacts) first and then run through the I-O model. This is done so that the basic I-O approach can be established to build upon for the more complex cases described below.

True indirect effects arise when electricity disruptions in some sectors are much higher than in other sectors and cause supply input *bottlenecks* other than for electricity. This can happen when a sector is heavily concentrated in one subregion that is especially hard-hit by an earthquake. The computation of this effect takes note that underlying the I-O model is the concept of the *fixed-coefficient* production function, i.e., output is dependent on the most limited input.[3] First, the initial vector of gross output losses due to the earthquake is examined to identify the sector with the largest potential output reduction, which in effect becomes the *constraining* input to other sectors. Then, all of the other X_j's are adjusted to the constraining sector's output reduction level. Of course, the constraining sector would be verified to ensure that it was really crucial to production. For example, if the entertainment or personal services sectors had the largest potential output reductions due to an electricity disruption, the analysis would proceed to the sector with the next highest ΔX_j. Effectively, the d_j for the constraining sector is used in Equation 7.3 for all sectors (except those non-crucial ones passed over).[4]

Resiliency bears on the computations in two ways. First, it affects the initial estimates of output reduction in each sector. Let r_{ej} represent the resiliency of sector *j* to electricity disruption, where $0 \leq r_{ej} \leq 1$. Then $1 - r_{ej}$ represents an "importance factor" that indicates the dependence of sector *j* on electricity. For example, an importance factor of 0.9 means that every 10% decrease in electricity available leads to a 9% decrease in a given sector's output. Second, it means less electricity is needed per unit of output (because of conservation potential, back-up power sources, etc.) and thus requires a decrease in the electricity input coefficient, which is denoted by a_{ej}. Thus, a modified matrix, A^* is substituted for A by multiplying the electricity input coefficient in each sector, a_{ej}, by its corresponding $1 - r_{ej}$ factor.[5]

These two effects are combined to modify Equation 7.2 as follows:

$$\Delta Y_j = (I - A_j^*)(1 - r_{ej}) d_{ej} w^s \overline{X} \qquad (i = 1\ldots21);\ (s = 1\ldots36) \quad (7.2a)$$

Thus far, the time dimensions of the analysis have not been explicit. As noted in the previous section, resiliency will change (usually decrease) over time. In addition, there will be a differential time path of restoration across electricity service areas. The aforementioned impact equations are, of course, still applicable, but they have to be run for several distinct time periods associated with parameter changes.

7.1.2 Analysis of Simulation Results

The basic I-O impact model from Chapter 2 was applied to the direct disruption estimates of Chapter 4, and simulations with and without input bottleneck effects were performed. Note that the analysis has not been able to include all of the factors affecting regional economic losses. First, there is likely to be significant damage to buildings, so that even with immediate restoration of electricity services, the economy would not likely revert to baseline production levels. Second, other lifeline services are also likely to be disrupted, and one needs to guard against double-counting.[6] The most extensive damage should be attributed to a "bottleneck" utility lifeline (in a manner analogous to the analysis of bottleneck economic sectors). Resiliency was probably understated by omitting its prospects with regard to the bottlenecked sector and by ignoring the possibility of importing more crucial goods and services. In addition, many sectors can make up lost production by working overtime shifts after electricity is restored. Finally, a shortened disruption period due to temporary repair measures was not considered. On the other hand, losses have been underestimated by not having data on transmission line and distribution line disruptions. In addition, damage to electric power can cause other types of losses such as gas line explosions and fires, as well as hampering fire fighting and other emergency responses. Overall, many of these factors offset each other, but it can be surmised that the loss estimates herein are definitely in the high-end range. Note also that the methodology can readily incorporate most of these omitted factors when data become available or can do so with some minor adjustments, as in the case of imports (see e.g., Boisvert, 1992 and Cochrane, 1997). Natural disaster impacts involve extreme complexities, which cannot be fully understood or modeled empirically at this time. Still, insight into an important piece of the puzzle can be provided.

Preliminary data used in these simulations are presented in the first four columns of each of Table 7.1 and Tables Appendix 7.A1-A4. Note that the final demand and output data are measured on a weekly basis. The changes in gross output ("X1—Reduction") column entries differ from table to table (period to period) because of restoration and resiliency changes over time.

For example, during the first week (Week 0), there was a maximum disruption for Shelby County (no EPSA had service restored). As shown in Table 7.1, the bottleneck sector is petroleum refining, which is highly concentrated in an EPSA that suffers the most severe disruption in the county. It is also a sector with a minimum of resiliency with respect to electricity inputs. For the simulation "Without Bottleneck" effects, gross output losses are the same as the (Direct) X1—Reduction (as discussed in the previous section) and amount to a total of 49.55% ($329 million) of baseline production in Shelby County. Bottleneck effects raise this disruption to 78.71%. Thus, the true indirect effect during Week 0 is 29.16% of gross output. Note also that the final demand numbers in this and other tables are not just the mechanism to initiate the I-O simulations, but also represent a measure of changes in gross regional product (GRP).

Simulation results for additional distinct time periods are presented in Tables 7.A1-A4 and contain some interesting insights. In comparison to Week 0, the Week 1 impacts "Without Bottlenecks" are less than the Week 0 impacts, but the simulations "With Bottlenecks" are greater, because of the potential for the bottleneck effect to worsen as resiliency deteriorates over time. Of course, the results signal the wisdom of choosing a new restoration time path, one that favors the EPSA in which the bottleneck occurs. This will be discussed at greater length in Section 7.2.

Non-bottleneck output reductions are reduced even further for the Weeks 2-3 results (see Table 7.A3), though the bottleneck results are the same as in Table 7.A1. Negative changes in final demand appear in Table 7.A2 stemming from enhanced production levels in various sectors that are not fully synchronized with intermediate output requirements, thus leaving more of the product available for final use.

Table 7.1 Final Demand and Gross Output Reductions for Shelby County During First Week of Electricity Disruption (all dollar figures in millions)

Sector	Final Demand (Y)	Gross Output (X)	X1 % Reduction w/o Bottleneck	X2 % Reduction w/ Bottleneck	Y1 Reduction	Y2 Reduction	X1 Reduction	X2 Reduction
Agriculture	$ 2.715	$ 3.898	40.17	78.71	$ 0.937	$ 2.003	$ 1.565	$ 3.069
Mining	0.683	0.763	20.32	78.71	0.128	0.536	0.155	0.601
Construction	39.710	47.231	41.14	78.71	15.647	31.259	19.429	37.175
Food Products	34.808	41.000	51.68	78.71	16.936	25.686	21.190	32.271
Nondurable Manufacturing	64.235	78.479	54.06	78.71	33.418	47.986	42.423	61.771
Durable Manufacturing	41.988	48.821	51.46	78.71	20.932	31.691	25.124	38.427
Petroleum Refining	2.888	8.115	78.71	78.71	3.530	1.312	6.388	6.388
Transportation	66.800	80.642	40.16	78.71	23.657	48.507	32.390	63.474
Communication	3.506	8.765	42.45	78.71	0.339	1.368	3.721	6.899
Electric Utilities	1.762	4.171	45.46	78.71	0.322	0.816	1.896	3.283
Gas Distribution	0.035	0.208	47.66	78.71	0.000	0.008	0.099	0.163
Water and Sanitary Services	0.610	1.027	47.95	78.71	0.152	0.280	0.492	0.808
Wholesale Trade	32.631	41.156	48.66	78.71	14.352	23.158	20.028	32.394
Retail Trade	50.419	55.987	48.80	78.71	14.409	23.183	27.321	44.067
F.I.R.E.	59.746	75.781	50.74	78.71	17.749	26.625	38.449	59.647
Personal Services	10.840	12.338	49.31	78.71	3.760	6.032	6.084	9.712
Business and Prof. Services	28.108	57.013	50.92	78.71	11.309	15.972	29.034	44.875
Entertainment Services	2.881	3.860	48.93	78.71	0.602	0.946	1.888	3.038
Health Services	27.496	27.848	54.54	78.71	8.999	12.143	15.189	21.919
Education Services	4.177	4.269	50.03	78.71	0.816	1.266	2.136	3.360
Government	53.850	62.098	54.38	78.71	26.532	37.493	33.767	48.877
Total	$529.887	$663.469			$214.524	$338.269	$328.769	$522.217
Weighted Average			49.55%	78.71%	40.48%	63.84%	49.55%	78.71%

Y1: Use of *(I-A)* vector and direct output reduction estimates to obtain a new final demand vector
Y2: Use of *(I-A)* vector and largest output reduction rate to obtain a new final demand vector

The bottleneck tightens slightly in Week 4. However, in Weeks 5-15, when power has been totally restored in all but one EPSA, the bottleneck sector changes to nondurable manufacturing. The bottleneck effects are still five times larger than the non-bottleneck results, but they amount to only a 3.70% reduction in gross output.

The results for the entire 15-week disruption period are presented in Table 7.2. Note that for this presentation, the final demand and gross output figures are on an annual basis because that is the standard time span for measuring economic changes. The results for the "W/O Bottleneck" case are an overall reduction final demand and gross output of 1.90% and 2.28%, respectively. The hardest hit sector in absolute terms is finance, insurance, and real estate (F.I.R.E.), with an output (sales) reduction of nearly $100 million (over and above property damage stemming from the earthquake). For the bottleneck simulations, the reductions in final demand and gross output are 6.97% and 8.95%, respectively. This means that indirect effects overall are 6.31% of gross output, or $2.2 billion. Overall, the bottleneck effects are almost four times the direct (and standard total) electricity disruption effects themselves.

Note that the choice of a 15-week restoration period is somewhat arbitrary (see Chapter 6), and that the impacts would have to be adjusted for other patterns. However, the methodology is sufficiently general to do this. Moreover, the interested reader could use the results presented in Tables 7.A1 to A4 to come up with rough estimates for alternative time periods. Finally, a major difference between stock and flow losses should be emphasized. Unlike building damages, output losses are directly dependent on the length of the restoration period.

7.2 Optimal Rationing of Scarce Electricity

7.2.1 Linear Programming

In the previous section, the economic impact of across-the-board cutbacks (*proportional rationing*) of electricity to each sector

Table 7.2 Annual Final Demand and Gross Output in Shelby County Following Electricity Lifeline Disruptions Over All Time Periods (in millions of dollars)

Sector	Baseline		w/o Bottleneck		w/ Bottleneck	
	Final Demand	Gross Output	Final Demand	Gross Output	Final Demand	Gross Output
Agriculture	$ 141	$ 203	$ 139	$ 199	$ 130	$ 185
Mining	36	40	35	39	32	36
Construction	2065	2456	2027	2410	1887	2245
Food Products	1810	2132	1783	2097	1664	1949
Nondurable Manufacturing	3340	4081	3228	3946	3068	3730
Durable Manufacturing	2183	2539	2134	2480	2003	2320
Petroleum Refining	150	422	123	389	143	386
Transportation	3474	4193	3428	4128	3198	3833
Communication	182	456	180	447	175	417
Electric Utilities	92	217	91	213	87	198
Gas Distribution	2	11	2	11	2	10
Water and Sanitary Services	32	53	32	52	30	49
Wholesale Trade	1697	2140	1671	2100	1565	1956
Retail Trade	2622	2911	2599	2859	2490	2661
F.I.R.E.	3107	3941	3059	3845	2956	3602
Personal Services	564	642	557	629	529	586
Business and Prof. Services	1462	2965	1437	2899	1371	2710
Entertainment Services	150	201	149	197	144	183
Health Services	1430	1448	1405	1409	1361	134
Education Services	217	222	216	218	210	203
Government	2800	3229	2735	3147	2587	2952
Total (15 weeks)	$27554	$34500	$27031	$33714	$25634	$31535
Weighted Avg. Reduction			1.90%	2.28%	6.97%	8.59%

in a given electric power service area (EPSA) was simulated. The alternative of *differential rationing* of available electricity is now considered to minimize total economic losses from an earthquake. Two simulations will be performed: 1) reallocation of electricity across sectors and subregions with the previous restoration pattern and 2) reallocation with an optimized restoration pattern.

This problem can be formulated as one of maximizing gross regional product given constrained electricity availability, constrained supplies of primary factors of production, and fixed technology. The equations are:

$$max \sum_j Y_j \tag{7.3}$$

subject to

$$Y_i = (I - A_{ij})X_i \qquad (i,j=1...21) \tag{7.4a}$$

$$\sum_j a_{ej} X_j^s + Y_e^s \leq X_e^s \qquad (s=1...36) \tag{7.4b}$$

$$\sum_s X_j^s = X_j \qquad (j=1...21) \tag{7.4c}$$

$$Y_e^s \leq \overline{Y}_e^s \qquad (s=1...36) \tag{7.4d}$$

$$X_j^s \leq \overline{X}_j^s \qquad (s=1...36),\ (j=1...21) \tag{7.4e}$$

$$Y_c \geq \alpha \overline{C}_c \qquad (c=4,7\text{-}9,19\text{-}21) \tag{7.4f}$$

$$Y_e^s \geq \beta \overline{C}_e^s \qquad (s=1...36) \tag{7.4g}$$

$$X_j^s, X_e^s \geq 0 \tag{7.4h}$$

where

$i,j(j=1...21)$:	economic sectors
$s(s=1...36)$:	electricity service areas
c :	necessities
e :	index of the electricity sector
Y_e^s :	final demand of electricity in area s after the earthquake

$\overline{Y}_e^s$:	final demand of electricity in area s before the earthquake
X_e^s:	total electricity available in area s after an earthquake
$\overline{C}_c, \overline{C}_e^s$:	personal consumption levels for necessities for the region and electricity by area before the earthquake
α, β:	desired minimum levels of personal consumption for necessities and electricity by area after the earthquake

and other variables are as previously defined.

The objective function maximizes the sum of the final demands over all sectors (equal to Gross Regional Product).[7] Equation 7.4a reflects the input-output technology matrix. Equation 7.4b specifies limitations on electricity availability in each serving area, s. Equation 7.4c sums sectoral gross outputs across all serving areas so the problem can be solved in an economy-wide context. Equation 7.4d imposes limits on electricity availability to final demand. Equation 7.4e limits the gross output of each sector in each serving area to not exceed its pre-earthquake level. Given that there are 36 serving areas and 21 sectors, Equation set 7.4e is composed of 756 individual equations![8] Equations 7.4f and 7.4g guarantee minimum levels of necessities (including electricity) for households. Equation 7.4h is simply the non-negativity conditions of an LP problem. The LP model minimizes losses by allocating scarce electricity in such a way as to favor those sectors that yield the highest contribution to GRP per unit of direct *plus* indirect use of electricity.

Several critical assumptions underlie the implementation of the model. In the absence of further information, it can only be assumed that productive capacity in each sector was fully utilized in Shelby County. That means that it is not possible for any sector to produce output flows during the recovery period larger than those before the event. Note that given the absence of data at this time, no capacity reductions have been inserted which would stem from damaged factories, for example. The model, however, is sufficiently general to allow for excess capacity or capacity reductions when data are available.

Employment data serve as the proxy for output in all sectors except electricity. MLGW does not have spatial billing information, and peak load information by service area had to be used. As noted above, the fraction of the peak load by area before the earthquake was used as a proxy of the correspondent fraction of utilization of electricity.

Household consumption of electricity by area is assumed to be bounded from above by the pre-earthquake final demand level. With the information at hand, the vector of final demand of electricity by area is unknown and cannot be consistently estimated as the difference between total utilization by area—computed using peak load information—and total intermediate consumption—computed combining technical coefficients of electricity use from the *A* matrix and output by area. Data come from three different sources, and the combination of simplifying assumptions lead to inconsistencies such as negative figures for final demand in heavily industrialized areas. Thus, the preliminary matrix of electricity flows by sector and area (including final demand as a sector) add to the totals given by the I-O information, but do not match total utilization of electricity by area. This rectangular matrix of electricity flows by area and sector is *balanced* by use of the RAS (biproportional matrix balancing) method (Bacharach, 1970).[9]

To impart greater realism into the model, lower bounds were added for personal consumption in sectors that are crucial during emergency management—*necessities*, as in Rose and Benavides (1997). These sectors are food, petroleum refining, transportation, communication, natural gas, water, health, education, and government. Given the area-specificity of personal consumption of electricity (i.e., residential use of electricity cannot be transported across subregions), the corresponding lower bounds for this commodity are area-specific.

7.2.2 Analysis of Simulation Results

Gross Regional Product in Shelby County was $27.6 billion in 1991, or $529.9 million per week. For the first week after an earthquake of M = 7.5 intensity, the weighted average availability factor for electricity across service areas is predicted to be reduced to 49.6% for the county as a whole, with an equivalent reduction in total gross output; inclusion of bottleneck effects increases losses to 78.7% (recall Table 7.1). In contrast, the linear programming model of electricity reallocation generates a total gross output reduction of \$89.5 million during Week 0, a 13.5% reduction from baseline, and a final demand (Gross Regional Product) reduction of \$66.2 million, a 12.5% reduction (see columns 3 and 4 of Table 7.3). Unlike the basically proportional decrease in electricity use across sectors in the I-O impact analysis of the preceding section, the benefit of the differential allocation is reflected in the fact that a reduction of \$1 in electricity translates into only a \$0.25 (12.5% ÷ 49.6% x \$1) reduction in Gross Regional Product.

Table 7.3 summarizes the recovery path of total gross output and Gross Regional Product that follows from the restoration pattern described in the previous chapters across EPSAs over the course of fifteen weeks. In general, the recovery path is monotonically increasing for most sectors. However, some major sectoral reallocations do occur. For example, comparing column 4 of Table 7.4 with column 7 of Table 7.2, it can be seen that electricity is shifted away from agriculture, food products, and durable manufacturing in favor of other sectors during Week 0. Note also that the unfavored sectors change over time as nondurable manufacturing and retail trade take on that role in Week 1.

In terms of personal consumption, the solution guarantees that households in each service area will receive at least 20% of the pre-earthquake level of electricity consumption at the instant of the earthquake. Services classified as necessities during an emergency are ensured 70% of the pre-earthquake level of personal consumption during Week 0 as well. These service levels improve as electricity availability increases.[10]

Total economic impacts of an electric utility lifeline disruption following a catastrophic earthquake in Shelby County under conditions of electricity reallocation are presented in Table 7.4, along with baseline levels and the results of other simulations. Overall, on a 52-week basis, final demand (GRP) and gross output are reduced by 0.59% and 0.62%, respectively (see columns 5 and 6), in contrast to corresponding losses of 1.90% and 2.28% under the ("Without Bottleneck") proportional reduction case (see columns 3 and 4). Moreover, even with the sectoral reallocation, output levels are higher for each sector than under that case with three minor exceptions. Overall, the improvement is 69% in final demand and 73% in gross output compared with the simulation of a proportional reduction of electricity across sectors.

Table 7.3 Final Demand and Gross Output for Shelby County After Optimal Electricity Reallocation Across Sectors: Selected Weeks (in millions of dollars)

Sector	Baseline Levels		Week 0 Reduction		Week 1 Reduction		Week 5-14 Reduction	
	Final Demand	Gross Output	Final Demand	Gross Output	Final Demand	Gross Output	Final Demand	Gross Output
Agriculture	$ 2.715	$ 3.896	$ 2.715	$ 3.170	$ 0.558	$ 0.726	$ 0.000	$ -0.004
Mining	0.683	0.763	0.000	0.033	0.166	0.191	0.000	0.005
Construction	39.710	47.231	0.001	0.576	0.001	0.394	0.001	-0.003
Food Products	34.808	41.000	20.808	23.828	12.464	14.490	0.000	0.000
Nondurable Manufacturing	64.235	78.479	0.000	3.848	6.590	9.368	1.064	1.155
Durable Manufacturing	41.988	48.821	41.988	44.679	19.964	21.323	0.106	0.119
Petroleum Refining	2.888	8.115	0.000	0.309	0.000	0.205	0.000	-0.006
Transportation	66.800	80.642	0.000	1.647	0.000	1.097	0.000	0.013
Communication	3.506	8.765	0.001	0.864	0.001	0.656	0.001	0.009
Electric Utilities	1.762	4.171	0.702	1.649	0.620	1.234	0.048	0.155
Gas Distribution	0.035	0.208	-0.001	0.037	-0.001	0.026	-0.001	0.005
Water and Sanitary Services	0.610	1.027	-0.001	0.070	-0.001	0.061	-0.001	0.011
Wholesale Trade	32.631	41.156	0.001	2.441	0.001	1.469	0.001	0.017
Retail Trade	50.419	55.987	0.000	0.357	13.753	14.080	0.000	-0.004
F.I.R.E.	59.746	75.781	0.001	1.196	0.001	1.132	0.001	0.004
Personal Services	10.840	12.338	0.000	0.249	0.000	0.181	0.000	0.007
Business and Prof. Services	28.108	57.013	-0.001	3.041	-0.001	2.616	-0.001	0.050
Entertainment Services	2.881	3.860	0.000	0.084	0.000	0.077	0.000	-0.004
Health Services	27.496	27.848	0.000	0.001	0.000	0.000	0.000	0.000
Education Services	4.177	4.269	0.000	0.028	0.000	0.017	0.000	-0.001
Government	53.850	62.098	-0.001	1.348	-0.001	1.108	-0.001	0.039
Total	$529.887	$663.469	$66.215	$89.454	$54.116	$70.451	$1.218	$1.565
Weighted Average			12.50%	13.48%	10.21%	10.62%	0.23%	0.24%

Table 7.4 Annual Final Demand and Gross Output in Shelby County Following Electricity Lifeline Disruptions Under Alternative Responses (in millions of dollars)

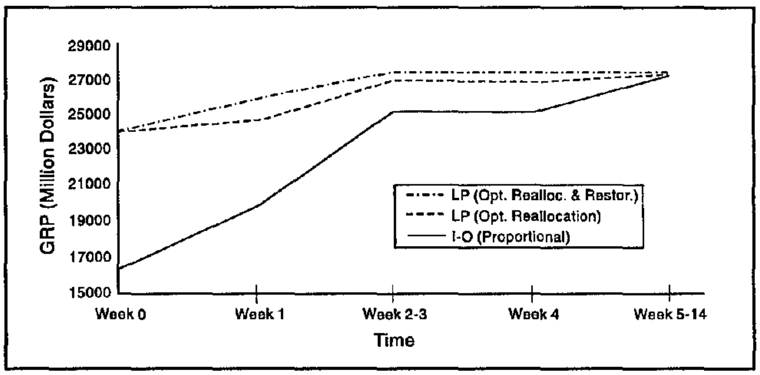
Sector	Baseline Levels		Proportional Reduction (I-O)		Optimal Reallocation (LP)		Optimal Reallocation and Restoration (LP)	
	Final Demand	Gross Output	Final Demand	Gross Output	Final Demand	Gross Output	Final Demand	Gross Output
Agriculture	$ 141	$ 203	$ 139	$ 199	$ 138	$ 199	$ 138	$ 199
Mining	36	40	35	39	35	39	35	40
Construction	2065	2456	2027	2410	2065	2455	2065	2455
Food Products	1810	2132	1783	2097	1777	2094	1780	2098
Nondurable Manufacturing	3340	4081	3228	3946	3311	4042	3340	4075
Durable Manufacturing	2183	2539	2134	2480	2102	2452	2121	2473
Petroleum Refining	150	422	123	389	150	421	150	422
Transportation	3474	4193	3428	4128	3474	4190	3474	4191
Communication	182	456	180	447	182	453	182	455
Electric Utilities	92	217	91	213	89	211	90	212
Gas Distribution	2	11	2	11	2	11	2	11
Water and Sanitary Services	32	53	32	52	32	53	32	53
Wholesale Trade	1697	2140	1671	2100	1697	2135	1697	2137
Retail Trade	2622	2911	2599	2859	2608	2897	2622	2911
F.I.R.E.	3107	3941	3059	3845	3107	3938	3107	3939
Personal Services	564	642	557	629	564	641	564	641
Business and Prof. Services	1462	2965	1437	2899	1462	2957	1462	2893
Entertainment Services	150	201	149	197	150	201	150	201
Health Services	1430	1448	1405	1409	1430	1448	1430	1448
Education Services	217	222	216	218	217	222	217	222
Government	2800	3229	2735	3147	2800	3226	2800	3227
Total	$27554	$34500	$27031	$33714	$27391	$34286	$27457	$34301
Weighted Avg. Reduction			1.90%	2.28%	0.59%	0.62%	0.35%	0.58%

The restoration of electricity service in each EPSA has thus far followed a reasonable rule—those substations with the lowest probability or extent of damage are restored first. This implicitly maximizes the amount of electricity restored per unit of repair dollar. However, some EPSAs potentially contribute more to GRP per unit of electricity than others, and this is a superior basis for identifying restoration priorities.

The optimal restoration pattern was simulated by using the shadow prices that stem from the dual of the LP solution referred to above. These shadow prices have the usual economic interpretation that Gross Regional Product would grow by the amount of the shadow price if one additional unit of electricity were available in the corresponding area and were utilized by the sector with the highest contribution to GRP (directly and indirectly) per unit of electricity.

Shadow prices for each week of the original LP simulation are presented inTable 7.A5. (These shadow prices represent the value of electricity when it is efficiently allocated.) In Week 1, restoration in EPSAs are substituted with the highest shadow prices in the original LP, but not exceeding the total megawatts of restored power (or repair dollars) of the original simulation.[11] This involves shifting efforts from EPSAs 1, 43, 64, and 72 to EPSAs 2, 4, and 13. This has the effect of yielding a restoration of GRP to 99.97% of baseline by Weeks 2/3 (in contrast to 98.05% in the original LP simulation and 91.96% in the I-O simulations of Section 7.1).

The timepaths for the three different types of responses are presented in Figure 7.1 and clearly depict the superiority of reallocating electricity both across sectors and across areas. The very nature of the strict concavity (i.e., it increases at a decreasing rate)



■ **Figure 7.1 Economic Recovery in Shelby County Under Alternative Responses** of the optimal recovery/restoration timepath is another indicator of its capability to optimize resource use over time. The shadow prices of the new LP simulation are in general lower than the shadow prices corresponding to the original LP solution. This is the dual expression of the result that society is better off in terms of GRP (the primal objective function). Note also that in the original LP, shadow prices increase in several areas between Weeks 0 and 1, which indicates that restoration is not optimal in the dynamic sense.[12]

The results on a sector-by-sector basis of the optimal restoration LP are also presented in the last two columns of Table 7.3. Note that some significant sector reallocations do take place in that the gross output of business and professional services is lower in the spatial/sectoral reallocation simulations than in the pure sectoral reallocation case.[13] Overall, final demand and gross output losses can be reduced to 0.35% and 0.58% of annual baseline levels. The GRP improvement is only 0.24%, or $66 million and only a modest improvement over the first LP case.. However, it is not difficult to imagine cases where this gap is likely to be much higher. Not taking advantage of these and the previously discussed reallocation opportunities results in losses as devastating as if the earthquake actually toppled the buildings in which the lost production would have originated.

7.2.3 POLICY IMPLICATIONS

Currently, in the electric utility industry, earthquake recovery plans are at a rudimentary stage with respect to economic criteria. Network managers' experience is limited to less sophisticated prioritization schemes for cases of brownouts or blackouts that do not require maintenance or restoration but orderly switching maneuvers. Given the short duration of the usual restoration efforts, typical contingency plans or algorithms are prioritized according to ease of restoration or size of subarea outage (equivalent to the *direct* impact on output), regardless of location. This would be clearly suboptimal as illustrated by the simulations.

The challenge for utilities such as MLGW is to implement a policy instrument to help attain a socially optimal outcome, which has been defined as minimizing Gross Regional Product losses. Implementation requires a mechanism to allocate scarce electricity supplies combining optimal pricing information (as given by the shadow prices) with a feasible form of load management.

Priority electricity service can be provided by a number of means. In the basic interruptible service contract, or market, alternative, each customer subscribes to a particular level of capacity *before* the earthquake. The customer pays an interruptibility premium, or capacity charge, for this amount and a usage fee for each unit actually consumed. If usage exceeds subscribed capacity, a circuit breaker, for example, could activate, curtailing additional consumption. Because customers differ according to their willingness to pay for electricity, those with a stronger demand would ideally buy larger fuse sizes. The utility has two roles in this scheme: to set usage and fuse prices so as to optimize resource allocation, and to guarantee enough capacity to meet the total required by customers' selections of fuse size. Load management is achieved by a decentralized system in which consumers ration themselves.[14]

In contrast to the above examples of price rationing, an alternative approach that gains significance as the size and duration of the disruption increases, is direct quantity rationing. This is sometimes overlooked as an option because of the technological features of electricity lifelines, i.e., unlike water, where the flow can be reduced, electric power is either on or off. Power system shut-off to individual customers is not always feasible, but there are other mechanisms. A good example stems from a recent response to the extreme winter in the eastern United States. In late January 1994, in Pennsylvania, utilities instituted *rolling blackouts*. In addition, the governor issued a decree (at the request of the utilities) closing state government offices and requiring nonessential industry to close down until the emergency was over.[15]

Overall rationing need not be heavy-handed; instead, it can be based on market incentives, such as pricing. However, policymakers still need to overcome the problem that occurs when customers make choices according to their own private costs and ignore social costs of disruptions, thus leading to market failure (see, e.g., Rose and Benavides, 1997). The use of shadow prices derived from a social cost optimizing methodology in place of interruptibility assessments made by individual firms under conditions of myopia (i.e., inability to calculate the general equilibrium ramifications of its actions) would be a first step. It may take a system of taxes/subsidies to induce firms to use them, however. It is also worthwhile to consider a combination of policy instruments, as, for example, the use of rationing for highest priority customers, such as hospitals and government emergency service departments, and pricing methods for the remainder of the economy.

7.3 CONCLUSION

A methodology for estimating the regional economic losses from earthquake damaged electric utility lifelines has been developed and applied. It is shown that ordinary input-output impact analysis would overestimate losses for simple cases and underestimate them when production bottlenecks occur elsewhere in the economy. It was also shown how losses could be reduced more than threefold by reallocating scarce electricity according to the results of a specially designed linear programming model and how losses could be reduced fourfold by optimizing the sequence of recovery of electricity substations according to the time trend of the LP model shadow prices. Given the probabilistic nature of the vunerability estimates of previous chapters and various additional uncertainties introduced in this one, the results are only intended as illustrative.

The models and results should be especially useful to economists, planners, and engineers in making decisions on mitigation measures and implementing recovery policies. Although the analysis was applied to an earthquake in Memphis, Tennessee, it can be readily generalized to other regions and to other types of natural hazards.

Table 7.A1 Total Impact Simulation for Shelby County: Week 1, Zone 1 Recovered (all dollar figures in millions)

Sector	Final Demand (Y)	Gross Output (X)	X1 % Reduction w/o Bottleneck	X2 % Reduction w/ Bottleneck	Y1 Reduction	Y2 Reduction	X1 Reduction	X2 Reduction
Agriculture	$ 2.72	$ 3.90	0.239	0.825	$ 0.52	$ 2.10	$ 0.93	$ 3.22
Mining	0.68	0.76	0.315	0.825	0.21	0.56	0.24	0.63
Construction	39.71	47.23	0.278	0.825	10.51	32.76	13.13	38.96
Food Products	34.81	41.00	0.347	0.825	11.39	26.92	14.23	33.83
Nondurable Manufacturing	64.23	78.48	0.371	0.825	23.04	50.30	29.12	64.75
Durable Manufacturing	41.99	48.82	0.308	0.825	12.28	33.21	15.04	40.28
Petroleum Refining	2.89	8.12	0.825	0.825	4.74	1.38	6.70	6.70
Transportation	66.80	80.64	0.273	0.825	16.11	50.85	22.01	66.53
Communication	3.51	8.77	0.295	0.825	0.35	1.44	2.59	7.24
Electric Utilities	1.76	4.17	0.495	0.825	1.02	0.86	2.06	3.44
Gas Distribution	0.03	0.21	0.522	0.825	0.04	0.01	0.11	0.17
Water and Sanitary Services	0.61	1.03	0.467	0.825	0.25	0.29	0.48	0.85
Wholesale Trade	32.63	41.16	0.313	0.825	9.10	24.28	12.88	33.96
Retail Trade	50.42	55.99	0.282	0.825	7.04	24.30	15.79	46.19
F.I.R.E.	59.75	75.78	0.317	0.825	10.16	27.90	24.02	62.52
Personal Services	10.84	12.34	0.291	0.825	2.03	6.33	3.59	10.18
Business and Prof. Services	28.11	57.01	0.329	0.825	7.03	16.73	18.76	47.03
Entertainment Services	2.88	3.86	0.287	0.825	0.25	0.99	1.11	3.18
Health Services	27.50	27.85	0.431	0.825	7.76	12.73	12.00	22.98
Education Services	4.18	4.27	0.323	0.825	0.48	1.33	1.38	3.52
Government	53.85	62.10	0.422	0.825	21.31	39.30	26.21	51.23
Total	$529.90	$663.49			$145.61	$354.563	$222.38	$547.38
Weighted Average			33.52%	82.50%	27.48%	66.91%	33.52%	82.50%

Y1: Use of $(I-A_i)$ vector and direct output reduction estimates to obtain a new final demand vector

Y2: Use of $(I-A_i)$ vector and largest output reduction rate to obtain a new final demand vector

Table 7.A2 Total Impact for Shelby County: Week 2-3, Zone 2-4 Recovered (all dollar figures in millions)

Sector	Final Demand (Y)	Gross Output (X)	X1 % Reduction w/o Bottleneck	X2 % Reduction w/ Bottleneck	Y1 Reduction	Y2 Reduction	X1 Reduction	X2 Reduction
Agriculture	$ 2.72	$ 3.90	0.043	0.825	$ 0.08	$ 2.10	$ 0.17	$ 3.22
Mining	0.68	0.76	0.107	0.825	0.07	0.56	0.08	0.63
Construction	39.71	47.23	0.068	0.825	2.45	32.76	3.21	38.96
Food Products	34.81	41.00	0.000	0.825	-0.25	26.92	0.00	33.83
Nondurable Manufacturing	64.23	78.48	0.145	0.825	9.82	50.30	11.38	64.75
Durable Manufacturing	41.99	48.82	0.076	0.825	2.98	33.21	3.71	40.28
Petroleum Refining	2.89	8.12	0.825	0.825	6.25	1.38	6.70	6.70
Transportation	66.80	80.64	0.040	0.825	1.94	50.85	3.23	66.53
Communication	3.51	8.77	0.092	0.825	0.31	1.44	0.81	7.24
Electric Utilities	1.76	4.17	0.000	0.825	-0.27	0.75	0.00	3.44
Gas Distribution	0.03	0.21	0.000	0.825	-0.02	0.01	0.00	0.17
Water and Sanitary Services	0.61	1.03	0.000	0.825	-0.06	0.29	0.00	0.85
Wholesale Trade	32.63	41.16	0.045	0.825	0.98	24.28	1.85	33.96
Retail Trade	50.42	55.99	0.044	0.825	0.27	24.30	2.46	46.19
F.I.R.E.	59.75	75.78	0.132	0.825	6.28	27.90	10.00	62.52
Personal Services	10.84	12.34	0.055	0.825	0.29	6.33	0.68	10.18
Business and Prof. Services	28.11	57.01	0.099	0.825	2.62	16.73	5.64	47.03
Entertainment Services	2.88	3.86	0.035	0.825	-0.08	0.99	0.14	3.18
Health Services	27.50	27.85	0.143	0.825	2.89	12.73	3.98	22.98
Education Services	4.18	4.27	0.047	0.825	-0.03	1.33	0.20	3.52
Government	53.85	62.10	0.118	0.825	6.07	39.30	7.33	51.23
Total	$529.90	$663.49			$42.59	$354.46	$61.57	$547.39
Weighted Average			9.28%	82.50%	8.04%	66.89%	9.28%	82.50%

Y1: Use of $(I-A_j)$ vector and direct output reduction estimates to obtain a new final demand vector
Y2: Use of $(I-A_j)$ vector and largest output reduction rate to obtain a new final demand vector

Table 7.A3 I-O Analysis for Shelby County: Week 4, Zone 2-4 Recovered, with Different Resilience at Week 4 (all dollar figures in millions)

Sector	Final Demand (Y)	Gross Output (X)	X1 % Reduction w/o Bottleneck	X2 % Reduction w/ Bottleneck	Y1 Reduction	Y2 Reduction	X1 Reduction	X2 Reduction
Agriculture	$ 2.72	$ 3.90	0.043	0.837	$ 0.08	$ 2.13	$ 0.17	$ 3.26
Mining	0.68	0.76	0.161	0.837	0.11	0.57	0.12	0.64
Construction	39.71	47.23	0.068	0.837	2.43	33.24	3.21	39.53
Food Products	34.81	41.00	0.000	0.837	-0.25	27.32	0.00	34.32
Nondurable Manufacturing	64.23	78.48	0.147	0.837	9.95	51.03	11.54	65.69
Durable Manufacturing	41.99	48.82	0.077	0.837	3.03	33.70	3.76	40.86
Petroleum Refining	2.89	8.12	0.837	0.837	6.34	1.40	6.80	6.80
Transportation	66.80	80.64	0.042	0.837	2.07	51.58	3.39	67.50
Communication	3.51	8.77	0.096	0.837	0.33	1.46	0.84	7.34
Electric Utilities	1.76	4.17	0.000	0.837	-0.28	0.73	0.00	3.49
Gas Distribution	0.03	0.21	0.000	0.837	-0.02	0.01	0.00	0.18
Water and Sanitary Services	0.61	1.03	0.000	0.837	-0.06	0.30	0.00	0.86
Wholesale Trade	32.63	41.16	0.046	0.837	1.01	24.63	1.89	34.45
Retail Trade	50.42	55.99	0.044	0.837	0.24	24.65	2.46	46.86
F.I.R.E.	59.75	75.78	0.139	0.837	6.73	28.31	10.53	63.43
Personal Services	10.84	12.34	0.055	0.837	0.29	6.42	0.68	10.33
Business and Prof. Services	28.11	57.01	0.099	0.837	2.58	16.98	5.64	47.72
Entertainment Services	2.88	3.86	0.035	0.837	-0.08	1.00	0.14	3.23
Health Services	27.50	27.85	0.144	0.837	2.90	12.91	4.01	23.31
Education Services	4.18	4.27	0.047	0.837	-0.03	1.35	0.20	3.57
Government	53.85	62.10	0.119	0.837	6.11	39.87	7.39	51.98
Total	$529.90	$663.49			$43.48	$359.59	$62.77	$555.35
Weighted Average			9.46%	83.70%	8.21%	67.86%	9.46%	83.70%

Y1: Use of $(I-A_i)$ vector and direct output reduction estimates to obtain a new final demand vector
Y2: Use of $(I-A_i)$ vector and largest output reduction rate to obtain a new final demand vector

Table 7.A4 I-O Analysis for Shelby County: Week 5-14, All Zones Recovered Except 6 (all dollar figures in millions)

Sector	Final Demand (Y)	Gross Output (X)	X1 % Reduction w/o Bottleneck	X2 % Reduction w/ Bottleneck	Y1 Reduction	FD-2 Reduction	X1 Reduction	X2 Reduction
Agriculture	$2.72	$ 3.90	0.013	0.037	$ 0.04	$ 0.09	$ 0.05	$ 0.14
Mining	0.68	0.76	0.000	0.037	0.00	0.03	0.00	0.03
Construction	39.71	47.23	0.009	0.037	0.40	1.47	0.43	1.75
Food Products	34.81	41.00	0.000	0.037	-0.02	1.21	0.00	1.52
Nondurable Manufacturing	64.23	78.48	0.037	0.037	2.64	2.26	2.90	2.90
Durable Manufacturing	41.99	48.82	0.016	0.037	0.70	1.49	0.78	1.81
Petroleum Refining	2.89	8.12	0.000	0.037	-0.03	0.06	0.00	0.30
Transportation	66.80	80.64	0.001	0.037	-0.03	2.28	0.08	2.98
Communication	3.51	8.77	0.006	0.037	0.02	0.06	0.05	0.32
Electric Utilities	1.76	4.17	0.000	0.037	-0.03	0.03	0.00	0.15
Gas Distribution	0.03	0.21	0.000	0.037	0.00	0.00	0.00	0.01
Water and Sanitary Services	0.61	1.03	0.000	0.037	-0.01	0.01	0.00	0.04
Wholesale Trade	32.63	41.16	0.002	0.037	-0.02	1.09	0.08	1.52
Retail Trade	50.42	55.99	0.003	0.037	0.03	1.09	0.17	2.07
F.I.R.E.	59.75	75.78	0.003	0.037	0.03	1.25	0.23	2.80
Personal Services	10.84	12.34	0.003	0.037	0.01	0.28	0.04	0.46
Business and Prof. Services	28.11	57.01	0.002	0.037	-0.13	0.75	0.11	2.11
Entertainment Services	2.88	3.86	0.004	0.037	0.00	0.04	0.02	0.14
Health Services	27.50	27.85	0.000	0.037	-0.06	0.57	0.00	1.03
Education Services	4.18	4.27	0.003	0.037	0.00	0.06	0.01	0.16
Government	53.85	62.10	0.000	0.037	-0.11	1.76	0.00	2.30
Total	$529.90	$663.49			$3.43	$15.88	$4.95	$24.54
Weighted Average			0.75%	3.70%	0.65%	3.00%	0.75%	3.70%

Y1: Use of $(I-A_r)$ vector and direct output reduction estimates to obtain a new final demand vector
Y2: Use of $(I-A_r)$ vector and largest output reduction rate to obtain a new final demand vector

Table 7.A5 Shadow Prices for Electricity by Service Area

Area	Week 0		Week 1		Week 2-3		Week 4		Week 5-14	
	Original	New	Original	New	Original	New	Original	New	Original	New
1	170.33	170.33	0	65.44	0	1	0	1	0	0
2	170.33	170.33	178.4	0	172.07	0.04	172.07	0.04	0	0
3	170.33	170.33	178.4	163.81	0	0	0	0	0	0
4	170.33	170.33	178.4	0	180.78	0	180.78	0	0	0
5	170.33	170.33	178.4	163.81	0	0	0	0	0	0
6	170.33	170.33	178.4	163.81	0	0	0	0	0	0
7	170.33	170.33	178.4	163.81	0	0	0	0	0	0
11	170.33	170.33	61.57	63.23	0	0	0	0	0	0
13	170.33	170.33	178.4	0	171.98	0	171.98	0	128.59	0
14	170.33	170.33	178.4	163.81	163.07	1	163.07	1	0	0
15	170.33	170.33	178.4	163.81	0	0	0	0	0	0
21	170.33	170.33	178.4	163.81	0	0	0	0	0	0
23	170.33	170.33	0	0	0	0	0	0	0	0
25	170.33	170.33	0	0	0	0	0	0	0	0
26	170.33	170.33	61.35	63.05	0	0	0	0	0	0
27	170.33	170.33	0	0	0	0	0	0	0	0
28	170.33	170.33	0	0	0	0	0	0	0	0
38	170.33	170.33	0	0	0	0	0	0	0	0

Area	Week 0		Week 1		Week 2-3		Week 4		Week 5-14	
	Original	New	Original	New	Original	New	Original	New	Original	New
41	170.33	170.33	1	63.05	0	0	0	0	0	0
42	170.33	170.33	0	0	0	0	0	0	0	0
43	170.33	170.33	0	63.05	0	1	0	1	0	1
44	170.33	170.33	0	0	0	0	0	0	0	0
45	170.33	170.33	164.53	163.81	0	0	0	0	0	0
46	170.33	170.33	100.95	97.15	0	0	0	0	0	0
47	170.33	170.33	0	0	0	0	0	0	0	0
48	170.33	170.33	1	63.05	0	0	0	0	0	0
49	170.33	170.33	178.4	163.81	0	0	0	0	0	0
55	170.33	170.33	0	0	0	0	0	0	0	0
61	170.33	170.33	178.4	163.81	0	0	0	0	0	0
64	170.33	170.33	0	63.05	0	1	0	1	0	0
66	170.33	170.33	0	0	0	0	0	0	0	0
67	170.33	170.33	178.4	163.81	167.17	1	167.17	1	0	0
68	170.33	170.33	0	0	0	0	0	0	0	0
71	170.33	170.33	0	0	0	0	0	0	0	0
72	170.33	170.33	0	63.05	0	1	0	1	0	0
74	170.33	170.33	0	0	0	0	0	0	0	0

NOTES

1. The approach taken herein is that of interindustry analysis (see the brief review in Chapter 2). Other approaches to estimating economic impacts of disasters are found in the literature. Regional econometric models, for example, have been successfully applied to various aspects of actual and simulated disaster impacts by Chang (1983), Ellson et al. (1984), and Guimaraes et al. (1993). However, this approach does not lend itself readily to tracing the linkage between lifelines and the regional macroeconomy. The analysis presented here differs from most of the econometric studies and some of the interindustry studies in that it simulates the impacts of a hypothetical event, as opposed to estimating the impacts of an actual disaster or of the reconstruction spending in its aftermath. The methodology is sufficiently general, however, to undertake both an ex ante and ex post impact analysis, as well as optimal planning. In the ex post context, actual data on lifeline outages can be used instead of engineering simulation data (see Rose and Lim, 1997).

2. The computations are performed with an I-O table closed with respect to (i.e., including) households. Those familiar with I-O analysis may find Equation 7.2 a bit unusual at first glance. The typical conversion of any individual sector's gross output into final demand is done by dividing the former by the element b_{jj}, a diagonal term of the closed Leontief Inverse (see, e.g., Miller and Blair, 1985). However, when more than one element is adjusted, there are interaction effects in the ensuing computations. Therefore, the row vector $(I - A_i)$ is used.

3. Note, there is strong disagreement about the realism of the fixed coefficient production function in general, but strong agreement of its relevance in the very short-run, such as the timespan of electricity outages stemming from earthquakes.

4. Note that the alternative is to use a *supply-side* input-output analysis (see, e.g., Davis and Salkin, 1984, for an application to water shortages). However, given the dispute over the conceptual soundness and accuracy of this approach (see, e.g., Oosterhaven, 1988; Rose and Allison, 1989), we have chosen to follow the less complicated procedure above.

5. In the short term, backup power, conservation, and similar responses require only an adjustment in the α_{ej}. For the case of substitution of other fuels for electricity, there would be a need to adjust other technical coefficients as well.

6. The methodology does take into account some, although not all, interactions between lifelines. For example, electricity is needed to pump water, and the model is able to provide a rough estimate of the ensuing direct losses to water lifeline capability and subsequent indirect effects for normal use. However, there are some extraordinary circumstances the model cannot account for, e.g., lack of power for pumping water may force the evacuation of upper floors of tall buildings, which cannot be protected from fire, thereby causing still further business disruptions.

7. For examples of other welfare criteria that might be used as the basis for allocating scarce lifeline resources, see Cole (1995). Note also that the constraints in the model also guarantee necessary amounts of basic necessities such as food and health services.

8. The specification of these equations is expedited by the formatting conventions of the General Algebraic Modeling System (GAMS) Software (Brooke et al., 1988) which was used for the simulations.

9. Each RAS iteration consists of first multiplying each row by the ratio of the desired and the current row totals, and then multiplying each column by the ratio of the desired and the current column totals. After each iteration, a decision was made to go ahead or to stop by checking the precision in the row totals. Under mild conditions (such as non-negativity of the initial table figures), the method converged quite rapidly to the desired precision. In essence, the RAS method enabled us to estimate the pre-earthquake vector of final demand of electricity by area, $\bar{y}_s^e$, and the matrix of technical coefficients of electricity by sector j and area s, a_{ej}^o. These coefficients are found after dividing the balanced matrix of electricity input flows by output in each sector and area. The deviations between elements of the matrix of a_{ej}^o and the counterpart a_j^e elements were minor.

10. These results can be contrasted with the implications of the 2-sector, 2-factor Rybczynski Theorem (see e.g., Silberberg, 1990). Theorem establishes that if the endowment of some resource (electricity) increases, the industry that uses that resource most intensively will increase its output while the other industry will decrease its output. In the case study, increments in electricity availability were accom-

panied by output additions in sectors that use electricity more intensively. However, output reductions were found only temporarily in Government. This is a typical interindustry effect: output from other industries (in turn inputs to other industries) increase as electricity availability improves. In the majority of the cases, increments in electricity were sufficient to generate an increase in output for all sectors. The exception reflects trade-offs in EPSAs where Government must compete with sectors using electricity most intensively, in the presence of uneven input increments.

11. For simplicity, a fixed total time to fully restore electricity in the region, a linear repair intensity, and equivalent restoration efforts by MW were assumed. This is equivalent to repairing a constant amount of MWs per week. Those MW are denominated in "repair dollars." With that in mind, the policy is: at each period, devote your efforts to restore those electricity power areas that yield the highest shadow price of electricity, such that the repaired MWs at each period do not add up to more than the repair intensity.

12. The shadow prices can take on three distinct sets of values: $\lambda \geq 1$, indicating that the availability of one more dollar of electricity is being used for intermediate goods production; $\lambda = 1$, implying the area is fully using its productive capacity and on additional unit of electricity goes directly to final demand; and $\lambda = 0$, indicating that the area is being provided with the pre-earthquake electricity services and thus this input is not locally scarce.

13. The small incremental improvement of the second LP simulation may be surprising at first glance. This is partly due to the spatial configuration of the MLGW electricity network. But more generally, it is due to the fact that the sectoral reallocations for the first LP simulations implicitly capitalize on most of the spatial reallocation possibilities of the problem at hand. It was expected that the substation restoration simulations would be more prominent in regions with less sectoral adjustment flexibilities, i.e., regions with less uniformly distributed sectors spatially or those with few sectors.

14. This scheme, however, must be supplemented by a contingent rule that will be put into operation when a supply shock reduces capacity beyond the rated fuse sizes of all customers. A simple and realistic modification to this scheme would be to introduce a load control strategy in which a customer continues to self-ration by purchasing a fuse, but the fuses can be activated by the electric utility when a capacity shortage occurs. In practice, however, customers wish to

"insure" some base level of power supply during the emergency. This would require a more complex design (Wilson, 1989), where the customer pays a premium depending on priority class. In general, the optimal allocation of electricity is more complicated than for water, probably the resource for which there has been the most advances in theory and practice in emergency situations (i.e., drought), as opposed to local distribution disruptions associated with earthquakes (see, e.g., Howitt et al., 1992; Zarnikau, 1994). Also, the allocation of water to meet broad social objectives is part of standard practice, in part, due to its common property resource characteristics. Both market and centrally administered rationing are found. Generally speaking, electricity lifeline and disaster managers can learn from these experiences.

15. The small incremental improvement of the second LP simulation may be surprising at first glance. This is partly due to the spatial configuration of the MLGW electricity network. But more generally, it is due to the fact that the sectoral reallocations of the first LP simulations implicitly capitalize on most of the spatial reallocation possibilities of the problem at hand. It was expected that the substation restoration simulations would be more prominent in regions with less sectoral adjustment flexibilities, i.e., regions with less uniformly distributed sectors spatially or those with fewer sectors.

Decision Support for Calamity Preparedness: Socioeconomic and Interregional Impacts

8

by Sam Cole

Natural disasters have their most severe impacts on isolated localities and small and impoverished communities. In the United States, natural disasters are a national problem, experienced at the local level (Berke and Beatley, 1992). For example, a major disaster like the "500-year" Midwest floods of 1993 had minimal impact at the national or even at the state level, yet many small communities may never be able to recover (Schnorbus et al., 1994). As a fraction of annual income or even normal business cycle swings, even Hurricane Andrew had modest impact on Dade County, Florida—yet South Dade County and Homestead were devastated. This specificity of the impacts demands that appropriate models of relatively small districts be available.

Disasters often impact most severely on poor and marginal populations (Ebert, 1982). In many cases, this can be traced to poverty and inappropriate development, such as inferior infrastructure or housing, or limited insurance and other defensive resources (Cuny, 1983). For similar reasons, disasters tend to impact small businesses more severely than large enterprises. Ideally, a model should describe the situation of these groups and activities explicitly, as well as their links with the wider economy and community.

Even when they are not impacted directly, people and businesses may be affected through damage to lifelines such as water supply or roads, or through indirect effects such as the loss of livelihood or markets. Even in aggregate, the indirect effects on a community are often far larger than the direct effects (Eguchi et al., 1993). Therefore, models need to be economy-wide, so as to account for all sectors of an economy and all segments of a population (see, e.g., NRC, 1992).

In general, the smaller a community, the greater will be the importance of its linkages to neighboring districts, and the more vulnerable it will be to damage to lifelines, such as power and water supplies, or transport and other communications. Moreover, the smaller a community the greater will be the spill-over effects to other communities, the more likely it is that neighbors also will be impacted directly by the disaster, or that feedback effects through their economies will be important (Brookshire and McKee, 1992). Thus, models must have an explicit account of a locality's links to its neighbors and the world beyond, and in many cases models must be multi-regional.

Disasters affect populations for an extended period of time. Most disasters and recovery activities operate on a variety of time scales that are characteristic of the physical, social, economic, and technological systems involved. As far as possible, it is necessary to represent these within a model, through the manner in which the impacts are calculated. Ultimately, the analysis of disasters presents an almost intractable network problem. Even so, one vital aspect of recovery programs or pro-active measures is to recognize that the vulnerability of the locality to disasters can be reduced through the application of various systems principles to the physical, economic, and social aspects of disaster preparedness (Shinozuka et al., 1995).

Recovery needs to be situated within the overall development process (Jones, 1981; Aysan et al., 1989). While the immediate priority must be to attend to the life-threatening consequences of the disaster (such as medical and shelter needs), it is also necessary to plan for an economic recovery which provides an opportunity to improve the quality of development if the hardship from future disasters is to be reduced (see, e.g., Kreimer and Munasinghe, 1990). In the past, victims and places often have been disadvantaged even further by deficient recovery programs. For this reason, disasters are best viewed as part of the development process, providing opportunities, as well as tragedy. A model based on this perspective must bring together relevant social and economic categories, so that both the damage caused by the disaster, and the proposed recovery strategy, can be assessed in the context of the long-term goals and institutional structures of the community.

Since natural disasters typically take place with rather little specific warning, planning tools should be adaptable to the situation of any community and type of damage, and should become available as soon as possible after the disaster, so that they can be used to evaluate alternative proposals for recovery, before irreversible commitments are made. Even after a disaster has occurred, there remains considerable uncertainty as to the extent of damage or the most appropriate recovery strategy, the model should be updatable and flexible, so as to respond to evolving community needs.

Thus, the need to provide analysis quickly, to provide models for small localities, describing specific sectors or lifelines, and particular types of household or community suggests a rather high level of empirical detail and technical sophistication. This conflicts with several practicalities, such as the availability of data, the understanding of complex systems, and the needs of the planning process. The last cannot be ignored since, when the separation between the modeling and policy making becomes too great, the modeling loses much of its potential use (United Nations, 1994). While many expert and other decision support systems have been developed in an attempt to bridge this gap (see, e.g., Harris and Batty, 1993), they have yet to confront the empirical and institutional chaos and complexity of much disaster planning. Even though the above is an incomplete list of the challenges for addressing the consequences of major natural disasters, it presents a formidable task for economic modeling.

8.1 MODELING ECONOMIC DISASTERS

The Social Accounting Matrix (SAM) used in this chapter is an extension of input-output analysis (see, e.g., Pyatt and Roe, 1977) to include more detailed institutional accounts such as household groups and external trading partners. SAMs are widely recommended as the core empirical device for national, regional and local planning (United Nations, 1994). Input-output models have been applied at the national or regional level for disaster assessment, with some recent efforts at the county level and small territories and islands (see Chapter 2, as well as Cole, 1993; 1995).

Social accounting models have the particular advantage that, given the requisite data, both the supply and the demand sides of the economy can be described as a network that can be mapped onto its physical and social counterparts. Because the nodes in the input-output tables represent localized production and consumption activities and the links show the flow of goods and services, such tables are especially appropriate for representing production, exchange, and consumption activities. This is necessary to describe and evaluate the consequences of specific types of damage in a useful fashion. The potential contribution of the methods adopted in this chapter is that it extends the possibilities for constructing detailed input-output type models for small localities, and for introducing fairly complex disaster and reconstruction scenarios, taking account of changes in the internal structure of the economy and its external links.

Most economic transactions depend directly on physical lifeline systems, for example, purchases of power and water by businesses and households, the trucking of goods between industrial areas and to markets, the flow of information within and without the region via telecommunication links. The impacts of earthquakes on lifeline systems involves not only earthquake resistant constructions of individual components but also system recovery with the aid of network redundancy, back-up facilities, and restoration work, that are to be followed by reconstruction and improvement for any future earthquake (Shinozuka et al., 1995). Because the nodes in the input-output tables represent localized production and consumption activities and the links show flow of goods and services, such tables are especially appropriate for representing production, exchange, and consumption activities.

8.2 Construction of the Many-Region Accounts

In order to address the complexity of the consequences of natural disasters, it is necessary to question some of the assumptions behind conventional input-output models, and to reformulate the construction and solution of these models. This is especially so when there is a complex of events arising from the partial failure of several activities, resulting in a more general failure of the economic network as a whole.

The earlier considerations place a very demanding set of requirements for model construction, especially when it is recognized that data at a small spatial scale are often restricted (for confidentiality and other reasons), and information on the direct effects of disasters are usually incomplete and collected in an ad-hoc fashion. On the other hand, the damage caused by a major natural disaster can affect the structure of an economy in dramatic ways (through the loss of entire industries or lifeline systems) so that even a model which captures the key features and linkages within an area's economy, before and after a disaster, and allows the broad outlines of a reconstruction strategy to be developed, can be useful. To this extent, the requirements on precision for the model may be somewhat less than for conventional economic impact calculations. Thus, the initial goal has been to make possible the rapid construction of a first-cut social accounts-based impact model for any locality within the United States, using readily available data, while providing for the subsequent improvement and extension of the model, to sub-county localities.

8.2.1 Development of the Model

Paradoxically, to develop the requisite analytic procedures for even a single county, it was necessary to first construct a detailed county-level many-region model of the entire United States. While this may appear a somewhat convoluted procedure, it provides the parameters necessary to estimate models for smaller, sub-county localities, and transactions between counties across the entire United States, providing indirect estimates of information that are otherwise not readily available. For the present exercise, a new national social accounting matrix has been assembled by combining two tables for the years 1982 (Hanson and Robinson, 1991; Reinert and Roland-Holst, 1992). This resulting matrix includes nine production sectors and seven factor and final demand categories with households divided by source of income: wages income, transfer payments, and rent.[1] The organization of the data in the United States and the addition of bilateral flows for the local-level social accounts are shown in Table 8.1. The table shows

Table 8.1 Local Area Social Accounting Matrix with Regional Transactions

Accounts		Locality 1: Domestic Production by Commodity Transaction	Locality 1: Factors	Locality 1: Households	Locality 1: Institutions	Locality 2: Domestic Production by Commodity Transaction	Locality 2: Factors	Locality 2: Households	Locality 2: Institutions	Neighbors: Neighboring Counties	Neighbors: Neighboring States and Regions	Other: Rest of U.S.	Other: Rest of World
Locality 1 Production	Agriculture, Forestry, Fishing Mining Construction Nondurable Manufacturing Durable Manufacturing Transportation, Communication, Utilities Trade F.I.R.E. Services	Domestic Inter-Sectoral Transactions in Locality 1 e.g. purchases of agricultural goods by food processors		Local Household Purchases e.g. local shopping		Exports from Locality 1 to Locality 2 = Imports from Locality 1 to Locality 2)		Final Demand Imports to Region		Exports to Other Regions			Over-seas Ex-ports and Pay-ments
Factors Households Institutions	Labor Property Transfer HH Wage HH Rent HH Government Capital	Domestic Factors and Institutions in Locality 1 e.g. wages to workers and entrepreneurs		Transfers and Other Payments e.g. welfare and taxes			Commuter and Other Transfers e.g. working in 2 and living in 1						
Locality 2 Production	Agriculture, Forestry, Fishing Mining Construction Nondurable Manufacturing Durable Manufacturing Transportation, Communication, Utilities Trade F.I.R.E. Services	Intermediate Imports to Domestic Production (Note: Exports from Locality 2 to Locality 1 = Imports from Locality 2 to Locality 1)		Final Demand Imports to Locality 1 from Locality 2		Domestic Inter-Sectoral Transactions		Local Purchases		Exports to Other Regions			
Factors Households Institutions	Labor Property Transfer HH Wage HH Rent HH Government Capital		Commuter and Other Transfers e.g. working in 1 and living in 2			Domestic Factors and Institutions		Transfers and Other Payments					
Neighbors	Counties Groups of Counties States Groups of States	Intermediate Imports to Locality 1	Other Commuting	Non-local Purchases e.g. mail order shopping and vacations		Intermediate Imports to Locality 2	Commuting		Non-local Purchases	Total Domestic Transactions and Bilateral Regional Trade			
Other	Rest of U.S.												
	Rest of World	Imports from Overseas to Locality 1				Imports from Overseas to Locality 2				Overseas Imports and Payments			

the expenditures (in columns) and receipts (in rows) for each group of economic actors, industry, services, factors, households, government, and rest-of-the-world. The multi-county tables include bilateral flows of these same items with neighboring counties (or localities), and with blocs of counties, states, and regions.

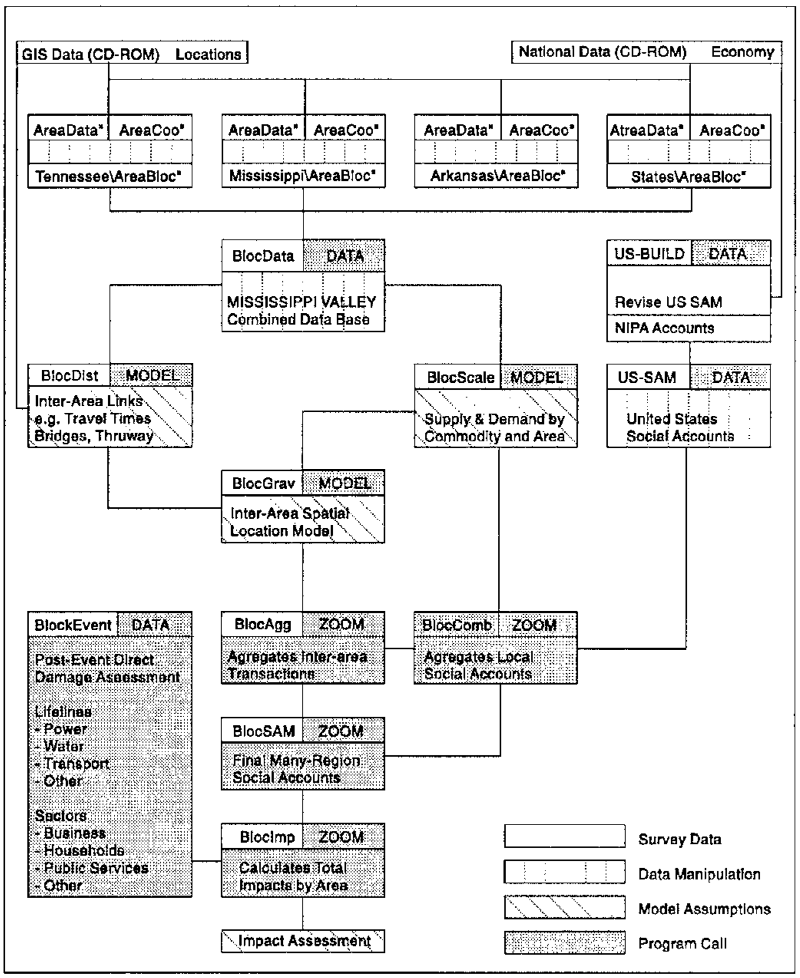
The basic techniques used to construct the county-level model are as follows. First, total supply and demand for each commodity and factor of production are estimated for every county and by scaling the accounts in the United States table using data from the U.S. Department of Commerce (1995). Second, the resulting supply-demand imbalances of each county are used to estimate the parameters of a spatial allocation model for each activity (Sen and Smith, 1995), and to provide bilateral interregional trade matrices. Third, these flows are combined with the scaled regional matrices to give the many-region social accounts. Finally, the accounts are aggregated so as to highlight the locality of immediate interest within an overall matrix of manageable size.

8.2.2 Representation as a Virtual GIS-based Model

The main principles of the approach have been piloted in earlier phases of the project (Cole et al., 1993; 1996b). Whereas these pilot studies required considerable "hands-on" treatment using some specially collected data, the present approach is largely automatic or mechanical using national data sets available in digitized form (e.g., on CD-ROM) with data handling and presentation manipulated through Geographic Information System (GIS) techniques, and using generalizable algorithms to scale and solve the models (Miller and Blair, 1985). This procedure is elaborated in Cole et al., (1993) and Cole (1992, 1996a).

Creating such a system in a GIS-like environment presents a major challenge. In principle, every locality described in the model is connected to every other through structure, time, and space—changing any variable in one region affects every variable in all other regions. Even though specific secular locality-to-locality impacts across large distances may be small (say, the impact of an earthquake in Memphis, Tennessee on Buffalo, New York), the combined effects onto entire regions or the nation of a local event are not. Representing these interregional impacts is also a challenge since most GIS deal well only with variations in structure, and do not deal well with time varying and place-to-place flows. Moreover, since many data are missing or must be estimated, there remains a question of how the empirical model, and the metadata that describe it, should be organized. Last, for real-world applications, the system should be manipulated via a relatively straightforward Decision Support System (DSS) interface (see Cole, 1996a).

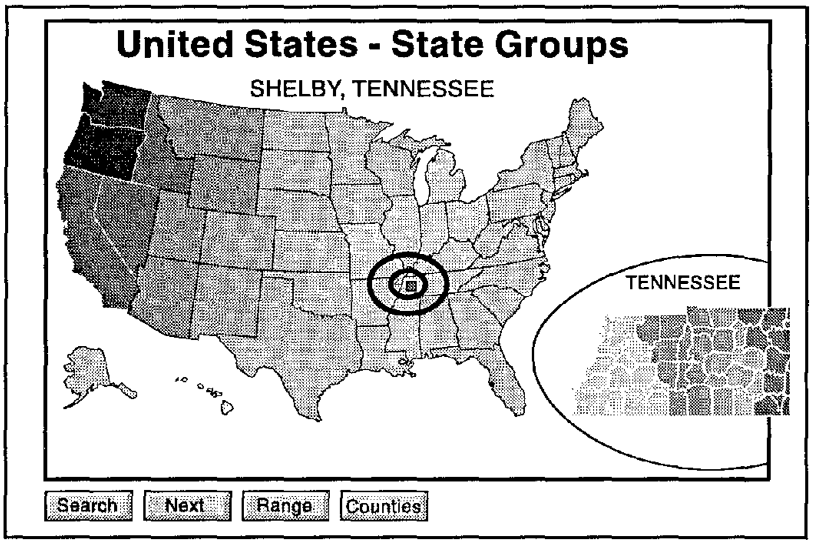
A model of the transactions between the 3,000 counties of the United States, each with up to 20 activities per region could require a matrix with 36×10^8 (a table covering several football fields!).



■ **Figure 8.1 Flow Diagram for Mississippi Valley Model Programs**

To deal with this vast amount of data, the system is organized as a "virtual model" whereby the many-region accounts are condensed to a set of basic data associated with each locality and a set of estimated parameters which allow selected local accounts to be re-constructed and solved as required. Thus, the system is designed to focus in on the segment of the matrix that describes the disaster area, in much the same way that a GIS system allows us to zoom a particular locality. A key task has been to devise appropriate estimation, and aggregation rules for this process, and a practical GIS interface.

The empirical implementation of model construction and application is carried out through a series of computer programs (see Cole, 1996a). The procedure falls into several steps, each comprising a group of macros (ie., computer program) for data preparation, model estimation, model assembly, and model solution.[2] This is summarized by the flow diagram in Figure 8.1. With this approach, the blocs of counties and states may be superimposed on the radial transportation networks which are ubiquitous in U.S. cities, or modified to correspond to other systems, so that the regional clusters correspond to nodes on the lifeline network. The selection of the target county, and neighbors, is automated via a GIS interface such as that shown in Figure 8.2.



■ **Figure 8.2 Interface for Selection of Target Locality and Aggregation of Neighbors**

8.3 MODEL SOLUTION

The social accounts provide a county-by-county pre-disaster picture of the network of domestic transactions and flows to and from neighboring regions. In a multi-region system, economic transactions spill over into neighboring regions and also feed back into the original economy. In the event of a disaster, some of the nodes and links in this many-region economic network are damaged, while others may take up the slack during the recovery. Because of this, the round-by-round process of spillover and feedback is disrupted and diminished. The method of solution used attempts to capture this process in a generalizable way.

8.3.1 DISTRIBUTED DISRUPTIONS, TRANSACTION COSTS AND UNCERTAINTY

The solution assumes that, even under normal circumstances, some proportion of transactions will be delayed unacceptably. Indeed, most economic actors attempt to reduce losses by maintaining buffer stocks, or concentrating their business in nearby markets. During a "disaster" — almost by definition — the proportion of failed transactions is increased beyond the capability of the normal system to cushion their livelihood. Thus, their economic losses increase dramatically.

The technique for solving the model rests on a time-dependent approach for conceptualizing input-output tables (Cole, 1988). The first important notion here is that the network of activities in any economy sets up a 'round-by-round' process that distributes income throughout the economy (see e.g. Miller and Blair, 1985). Thus, a change anywhere in the economy is magnified and transmitted throughout the community (and in some measure, throughout the world). This is the basis of the multiplier effect, that underlies all input-output type calculations, and provides an especially useful way of conceptualizing the propagation of events through structure, time, and space. The second underlying idea is that all economic processes involve a characteristic transaction lag — reflecting the time taken to design, finance, transport or produce goods, or simply to adjust to new circumstances (see ten Raa, 1986; Cole, 1988).[3]

Typically, input output models are used to simulate events that are relatively simple compared to the circumstances of a major disaster. Nonetheless, many changes may be simulated by "mapping" details of a disaster and the proposed recovery strategy onto the social accounts in an appropriate manner. Damage is introduced into the model via an Event Accounting Matrix (EAM) that records the intensity of the impacts on each activity and transaction and the response (or recovery rate) of each activity or transaction (see Cole et al., 1993).[4]

8.4 Memphis-Mississippi Valley Model

8.4.1 Memphis Region

The Mississippi Valley, centered on Memphis, Tennessee, provides the example in this chapter. The Memphis metropolitan region lies at the intersection of three States — Tennessee, Mississippi, and Arkansas. Given the great distance to the nearest cities of comparable size, Memphis might be considered the metropolitan center for as many as one hundred counties. The largest county, Shelby, contains about 80% of the region's business and population within counties which are proximate to Memphis. Memphis itself accounts for about 20% of the Shelby economy. The next largest nearby counties are De Soto in Mississippi and Mississippi in Arkansas, each with about 4% of the region's economy (U.S. Department of Commerce, 1994).

Table 8.2 compares the size, economic structure and income distribution across the counties of the region. It shows that service and lifeline sectors are concentrated in Shelby (19 and 53% of the county's total income). Shelby is a transportation center for the region. Other counties display a concentration of manufacturing activities (73% in Lauderdale, and 60% in Tipton, Tennessee), or agricultural activities (26% in Tunica, Mississippi). These variations, which are the result of many factors, indicate a good deal of trade between the counties. Similarly, in the counties adjacent to

Table 8.2 Relative Size and Composition of Memphis Region Counties

Items	Shelby TN	Tipton TN	Crittenden AR	De Soto MS	Fayette AR	Mississippi AR	Marshall MS	Lauderdale TN	Tate MS	Tunica MS
Share of Regional Economy										
Production	85%	1.2%	2.0%	3.5%	1.0%	4.1%	0.8%	1.5%	0.8%	0.3%
Value Added	82%	1.8%	2.7%	4.1%	1.1%	4.5%	1.0%	1.5%	1.0%	0.4%
Household Income	79%	2.6%	3.2%	5.4%	1.6%	3.5%	1.6%	1.4%	1.3%	0.5%
Composition of Economy										
Farming	2%	0%	4%	0%	4%	7%	3%	4%	3%	26%
Manufacturing	27%	60%	36%	66%	65%	66%	60%	73%	56%	26%
Lifelines	19%	4%	15%	6%	3%	4%	6%	4%	7%	5%
Services	53%	36%	45%	29%	28%	23%	31%	19%	34%	44%
Compos. of Household Income										
Transfer HH	16%	20%	18%	12%	22%	21%	24%	27%	21%	27%
Wage HH	64%	68%	70%	76%	65%	65%	64%	58%	64%	43%
Rent HH	20%	12%	12%	12%	13%	15%	12%	16%	15%	31%

Note: Farming (Agriculture, Forestry and Fishing), Manufacturing (Mining, Durable, Nondurable), Lifelines (Transportation, Utilities and Communication), Services (Commerce, F.I.R.E., Services)

Shelby, the share of production in the region as a whole is typically about half their share of household income, indicating a high level of commuting into Memphis. The composition of household income also varies across counties, for example, the share of wage income in Tunica is relatively low (reflecting its depressed rural economy), while Shelby is an employment and entrepreneurial center. Such data provide the empirical basis for the virtual model.

8.4.2 Memphis Accounts

The method described earlier is used to estimate a 50 county and cluster model focused on the Memphis region economy. This gives the transactions between the various production and households within the city of Memphis, and Shelby, and Crittenden counties, and between these localities and surrounding counties and states to be used in the impact calculations. Thirty individual counties in Arkansas, Mississippi and Tennessee, that are in the vicinity of Memphis are treated individually. The blocs of counties and states are superimposed on the transportation networks which in Memphis are roughly East-West and North-South. The final table is then focused on particular counties, or groups of counties, in this case those in the vicinity of Memphis.

The result is shown in Table 8.3, the county table for Shelby remains in full detail (i.e. with the same domestic transactions displayed as for the consolidated United States accounts shown earlier). The accounts for the immediate neighbor counties — Tipton, Fayette, and Lauderdale also in Tennessee; Crittenden and Mississippi in Arkansas; and De Soto, Marshall, Tate, and Tunica in Mississippi — are each consolidated to show only their aggregate domestic accounts and their imports from and exports to Shelby for each commodity and factor. Regional imports and exports are aggregated so that exports from production sectors are individual commodities, and imports to production sectors and to final demand are bundles of commodities.

The table shows the estimated flows of income through commuting and lifeline-related activities between the counties in the vicinity of Memphis. The data along the diagonal show transactions within the counties. For example, local wage and lifeline transactions within Shelby are $11,007 million and $3,354 million, respectively. The estimates for commuting show that all

Table 8.3 Local Area Social Accounting Matrix with Regional Transactions

Memphis	1994	Ag., For., Fishing	Mining	Construction	Nondurable Manufacturing	Durable Manufacturing	Trans., Comm., Utilities	Trade	F.I.R.E.	Services	Labor	Property	Transfer HH	Wage HH	Rent HH	Government	Capital
Accounts	$million	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Domestic Production by Commodity Transactions									Factors		Households			Institutions	
Agriculture, Forestry, Fishing	1	0.5	0.0	0.0	0.2	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.4	0.0
Mining	2	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction	3	0.0	0.0	0.0	0.0	0.1	1.9	0.2	3.4	1.9	0.0	0.0	0.0	0.0	0.0	6.9	13.9
Nondurable Manufacturing	4	0.1	0.0	0.3	0.4	0.2	0.8	0.2	0.3	3.5	0.0	0.0	0.3	0.6	0.1	0.4	0.0
Durable Manufacturing	5	0.0	0.0	3.0	0.1	3.0	0.9	0.2	0.2	4.5	0.0	0.0	0.3	0.7	0.1	2.6	6.0
Trans., Communication, Utilities	6	0.2	0.0	0.8	0.4	1.1	9.1	2.4	3.8	11.3	0.0	0.0	1.1	2.1	0.3	2.8	0.1
Trade	7	0.2	0.0	2.7	0.3	1.0	1.0	0.6	0.7	5.2	0.0	0.0	1.4	2.8	0.4	0.7	0.4
F.I.R.E.	8	0.7	0.0	0.8	0.2	0.8	3.1	5.0	4.4	19.6	0.0	0.0	4.9	9.7	1.2	2.4	0.4
Services	9	0.7	0.0	9.5	1.7	5.0	13.7	24.6	42.9	109.3	0.0	0.0	12.0	23.9	3.0	201.3	0.0
		Domestic Factors and Institutions											Transfers and Other Payments				
Labor	10	4.0	0.5	92.1	13.8	74.8	223.2	181.7	238.0	1455.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Property	11	12.5	1.5	15.0	9.2	12.2	208.5	65.9	535.5	385.3	0.0	0.0	2.1	6.1	1.5	88.7	0.0
Transfer HH	12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	496.4	0.0
Wage HH	13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	325.1	0.0	0.0	0.0	0.0	0.0	0.0
Rent HH	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0
Government	15	1.0	0.4	3.7	2.6	5.1	37.7	60.9	125.9	36.7	342.2	51.2	0.0	34.2	17.5	0.0	112.5
Capital	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	306.2	0.7	7.0	2.9	0.0	0.0
	17	Intermediate Imports to Domestic Production											Final Demand Imports to Region				
Rest of Shelby TN	18	7	0	46	12	34	80	53	95	302	1261	108	38	77	9	307	91
Tipton TN	19	0	0	1	0	0	1	0	1	2	16	1	0	1	0	2	2
Crittenden AR	20	0	0	1	0	0	1	0	1	3	15	1	0	1	0	3	1
De Soto MS	21	0	0	1	0	1	1	0	1	3	16	2	0	1	0	3	3
Fayette TN	22	0	0	0	0	0	0	0	0	1	7	1	0	0	0	1	1
Mississippi Arkansas	23	0	0	1	0	1	1	0	1	3	8	1	0	1	0	2	2
Marshall MS/Tate MS	24	1	0	6	2	6	11	3	6	27	41	17	3	6	1	16	17
Lauderdale TN/Tunica MS	25	1	0	9	2	8	11	4	8	35	62	19	4	8	1	23	22
Haywood TN/Cross, AR	26	1	0	9	2	8	12	5	9	37	57	21	4	9	1	25	24
ARKA, BENT, BOON, etc.	27	0	0	1	0	1	1	0	1	3	3	2	0	1	0	2	2
USA, MS, OK	28	1	0	7	2	6	14	4	7	32	13	24	4	7	1	17	17
TENN, ANDE, BLOU, etc.	29	0	0	1	0	1	2	1	1	5	4	3	1	1	0	3	4
USA, AL. GA	30	1	0	7	3	7	13	4	9	38	14	22	4	9	1	19	20
USA, LA	31	0	0	2	1	2	8	2	4	13	7	9	1	3	0	8	8
TN, CART, COCK, etc.; USA AL, etc.	32	3	0	18	6	16	31	9	19	81	17	65	9	18	2	42	51
USA, HI, TX	33	1	0	9	4	8	26	5	11	44	15	31	5	10	1	25	27
USA, CT, DE, etc.	34	5	0	40	13	36	62	22	41	192	37	156	22	44	5	93	107
Row	35	2	0	13	4	12	23	5	10	49	0	0	5	10	1	28	26
Total		45	3	301	83	254	799	461	1179	2905	2261	845	124	294	52	1422	558

Memphis		Rest of Shelby TN	Tipton TN	Critten-den AR	DeSoto MS	Fayette TN	MS AR	Marshall MS/Tate MS	Lauder-dale TN	Haywood TN	ARKA, BENT, etc.	USA, MS OK	TN, ANDE, BLOU, etc.	USA, AL, GA	USA, LA	TN, CART, COCK, etc.	USA, HI, TX	USA, CT, DE, etc.	Row
Accounts	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
		Commodity Exports from Locality to Other Regions																	
Agriculture, Forestry, Fishing		16	0	0	0	0	0	2	3	3	0	3	1	3	1	3	3	6	4
Mining		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Construction		97	1	1	1	0	1	13	18	21	2	15	4	14	8	16	17	23	0
Nondurable Manufacturing		49	0	0	1	0	0	5	7	9	1	6	2	6	3	7	7	9	4
Durable Manufacturing		121	1	1	2	1	2	16	24	26	2	17	5	18	12	21	22	29	25
Trans., Communication, Utilities		200	2	2	3	1	2	27	38	42	4	27	9	28	16	40	29	63	43
Trade		146	2	2	3	1	2	18	26	27	3	17	5	16	10	20	17	31	33
F.I.R.E.		437	4	5	0	2	4	41	63	61	6	32	12	30	21	36	34	39	43
Services		1578	17	18	21	8	17	69	131	105	9	22	9	21	13	19	19	30	53
		Commuting and Other Transfers																	
Labor															0	0	0	0	0
Property		0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
Transfer HH		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wage HH		594	3	4	4	1	4	14	27	25	2	6	2	6	3	6	6	12	0
Rent HH		26	0	0	0	0	0	4	6	6	1	4	1	4	2	5	5	5	0
Government		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capital		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Net Total Domestic Transactions and Bilateral Trade of Other Regions																	
Rest of Shelby TN		24478	124	137	160	63	149	1038	1654	1669	155	875	274	869	530	1060	1003	1493	1753
Tipton TN		147	133	6	7	5	13	60	101	109	9	47	15	46	29	57	57	78	32
Crittenden AR		149	6	266	15	3	12	80	140	133	13	63	20	65	37	74	69	115	51
De Soto MS		183	7	15	504	5	12	130	207	184	17	103	28	104	60	114	113	170	98
Fayette TN		79	5	4	6	81	6	56	84	89	7	43	12	42	27	50	51	67	28
Mississippi Arkansas		141	9	9	10	4	506	115	191	208	20	100	35	102	64	131	127	186	128
Marshall MS/Tate MS		1171	55	77	128	47	127	148948	3664	4966	416	2966	778	2787	3207	5209	10210	4665	8252
Lauderdale TN/Tunica MS		1539	77	113	169	59	189	3029	47871	4866	436	4063	770	4340	1986	3524	3578	5117	4487
Haywood TN/Cross, AR		1609	87	113	154	66	208	4266	5165	101688	649	3137	998	3172	2372	4392	4967	6017	6543
ARKA, BENT, BOON, etc.		130	6	9	13	4	16	324	392	580	7696	305	216	356	187	458	377	1042	704
USA, MS, OK		1268	57	80	121	44	127	3624	6189	4602	497	400604	960	8659	3874	5531	5455	7296	17269
TENN, ANDE, BLOU, etc.		210	10	14	20	7	27	540	639	816	200	525	30986	590	358	981	769	1656	1942
USA, AL, GA		1392	63	90	133	47	141	3678	7199	5123	634	9404	1180	547074	3347	6010	5393	10262	22938
USA, LA		560	25	34	49	19	57	2788	2092	2445	218	2728	454	2215	158650	3569	4636	3159	6732
TN, CART, COCK, etc.; USA AL, etc.		3206	146	195	276	107	348	13500	11052	13636	1571	11981	3806	11991	11051	4499341	29676	22688	162350
USA, HI, TX		1865	83	111	158	62	196	15661	6539	9001	763	6724	1713	6271	8227	16960	1042040	10624	38857
USA, CT, DE, etc.		7276	333	475	645	234	786	19142	25513	30545	5737	24812	10430	32179	14772	36220	28673	8005087	300213
Row		1849	48	67	113	35	126	8886	4749	6942	755	18617	2101	24640	8106	179607	43850	321030	45835
Total		50520	1303	1849	2718	910	3079	226072	123784	187926	19822	487244	54824	645649	216972	4763461	1181204	8400996	618416

■ Table 8.3 Local Area Social Accounting Matrix with Regional Transactions (continued)

Domestic Accounts Parameters

	Account	Fit	Distance	Scale	Local
1	Agriculture, Forestry, Fishing	18%	0.7	0.7	2.0
2	Mining	12%	0.7	0.8	2.0
3	Construction	15%	0.7	0.8	2.0
4	Nondurable Manufacturing	17%	0.7	0.8	2.0
5	Durable Manufacturing	23%	0.7	0.7	2.0
6	Transportation, Communication, Utilities	19%	0.7	0.7	2.0
7	Trade	15%	0.7	0.7	2.0
8	F.I.R.E.	15%	0.8	0.8	2.0
9	Services	16%	1.1	0.7	2.0
10	Labor	14%	1.2	0.6	2.0
11	Property	10%	0.7	0.8	2.0
12	Transfer HH	11%	0.7	0.7	2.0
13	Wage HH	14%	1.2	0.6	2.0
14	Rent HH	10%	0.7	0.8	2.0
15	Government	13%	0.7	0.8	2.0
16	Capital	17%	0.7	0.7	2.0

Neighboring Counties and Blocs

1	Memphis	33	Jackson, Arkansas
2	Rest Shelby, Tennessee	34	Alcorn, Mississippi
3	Tipton, Tennessee	35	Lake, Tennessee
4	Crittenden, Arkansas	36	Monroe, Arkansas
5	DeSoto, Mississippi	37	Pontotoc, Mississippi
6	Fayette, Tennessee	38	Obion, Tennessee
7	Mississippi, Arkansas	39	Lawrence, Arkansas
8	Marshall, Mississippi	40	Henderson, Tennessee
9	Lauderdale, Tennessee	41	Prentiss, Mississippi
10	Tate, Mississippi	42	Tallahatchie, Mississippi
11	Haywood, Tennessee	43	Miss Itaw, Lee, Tish
12	Tunica, Mississippi	44	Arka Rand
13	St. Francis, Arkansas	45	Tenn Weak
14	Poinsett, Arkansas	46	Miss Boli, Hump, Issa, Lefl, Shar, Sunf, Wash, Yazo
15	Cross, Arkansas	47	Arka Arka, Arka, Clev, Conw, Dall, Faul, Gran, Hot, Jeff, Lin
16	Benton, Mississippi	48	Miss Atta, Calh, Carr, Chic, Choc, Clay, Gren, Holm, Kemp, Lea
17	Hardeman, Tennessee	49	Arka Baxt, Cleb, Fult, Inde, Izar, Mari, Pope, Sear, Shar, Ston
18	Crockett, Tennessee	50	Tenn Bent, Carr, Chea, Deca, Dick, Gile, Hard, Henr, Hick, Hou
19	Lee, Arkansas	51	Arka Ashl, Brad, Chic, Desh, Drew
20	Dyer, Tennessee	52	Arka Unio
21	Lafayette, Mississippi	53	Tenn Tenn, Bedf, Bled, Cann, Clay, Coff, Cumb, Davi, Deka, Fra
22	Madison, Tennessee	54	Miss Adam, Clai, Copi, Fran, Hind, Jeff, Linc, Warr,
23	Tippah, Mississippi	55	Arka Bent, Boon, Carr, Craw, Fran, John, Madi, Newt, Wash
24	Greene, Arkansas	56	USA Miss, Okla
25	Union, Mississippi	57	USA Kent
26	Woodruff, Arkansas	58	Tenn Ande, Blou, Brad, Camp, Clai, Fent, Grai, Jeff, Knox, Loud, M
27	McNairy, Tennessee	59	USA Alab, Geor
28	Chester, Tennessee	60	USA Loui
29	Quitman, Mississippi	61	Tenn Cart, Cock, Gree, Hamb, Hanc, Hawk, John, Sull, Unic, Was
30	Gibson, Tennessee	62	USA Hawa, Texa
31	Coahoma, Mississippi	63	USA Conn, Dela, Flor, Illi, Indi, Mass, Mary, Main, Mich, Nort, New
32	Phillips, Arkansas	64	USA Alas, Ariz, Cali, Colo, Iowa, Idah, Kans, Minn, Mont, Nort, Ne

counties provide a net flow of labor to Shelby. For example, commuters from Crittenden earn $83 million in Shelby county, while only $29 million comes from commuting from Shelby to Crittenden. In general, the smaller counties, and those closest to Memphis have the highest level of commuting. For example, almost as many residents of Tunica commute to Shelby, as live and work in Tunica. For lifeline activities (predominantly transport, but including communication, and utilities combined), the flow is reversed and Shelby is a net exporter. In general, the smaller the region, the greater will be the mismatches between demand and supply of commodities and factors.

8.5 Application of the Decision Support System

8.5.1 Event Accounting Matrix

The damage sustained during the disaster, and also the subsequent recovery measures are introduced into the model via an Event Accounting Matrix (EAM), which maps the estimates of the direct economic onto the pre-disaster social accounts. Hypothetical events have been used to construct lifeline vulnerability functions and estimates of likely direct and indirect damage to the regional economy (e.g. NEHRP, 1992). In particular, most of the electricity supplied to these counties comes from the Tennessee Valley Authority (TVA) via a number of gate stations via transmission lines. The series of fragility models for the Memphis region to assess the vulnerability of the electricity lifeline systems as a result of substation failure, power imbalance, or loss of connectivity presented in Chapter 3 are embodied in the estimates of direct damage presented in Chapter 6 and utilized to estimate indirect impacts in Shelby County alone in Chapter 7.

8.5.2 Base Scenario

These damage estimates are allocated to the sectors described in the multi-county model to provide the "base scenario" given in the Event Accounting Matrix (EAM) shown in Table 8.4. This pro-

Table 8.4 Scenario - Output Disruption Event Accounting Matrix

Shelby, TN										
Timing of Event	**Base**					**Optimal**				
Event Start	1994.1	1994.0	1995.0	1994.0	1995.0	1994.1	1994.0	1995.0	1994.0	1995.0
Event Stop	1995.5	1995.0	1995.5	1995.0	1995.5	1995.5	1995.0	1995.5	1995.0	1995.5
Sector										
Agriculture, Forestry, Fishing		1.6	1.1				1.6	1.1		
Mining		0.4	0.3				0.5	0.3		
Construction		23.8	15.9				1.2	0.8		
Nondurable Manufacturing		59.4	39.6				71.4	47.6		
Durable Manufacturing		26.9	18.0				2.1	1.4		
Transportation, Communication,Utilities		43.6	29.1				53.8	35.9		
Trade		49.8	33.2				58.3	38.8		
F.I.R.E.		35.9	23.9				1.5	1.0		
Services		44.1	29.4				1.8	1.2		
Labor										
Property										
Transfer HH										
Wage HH										
Rent HH										
Government		32.3	21.5				0.9	0.6		
Capital										

Crittenden, AR										
Timing of Event	**Base**					**Optimal**				
Event Start	1994.1	1994.0	1995.0	1994.0	1995.0	1994.1	1994.0	1995.0	1994.0	1995.0
Event Stop	1995.5	1995.0	1995.5	1995.0	1995.5	1995.5	1995.0	1995.5	1995.0	1995.5
Sector										
Agriculture, Forestry, Fishing				0.1	0.1				0.1	0.1
Mining				0.9	0.6				0.0	0.0
Construction				0.4	0.2				0.4	0.2
Nondurable Manufacturing				1.4	0.9				1.1	0.7
Durable Manufacturing				0.9	0.6				1.0	0.6
Transportation, Communication,Utilities				1.0	0.7				1.1	0.7
Trade				1.2	0.8				1.0	0.6
F.I.R.E.				0.6	0.4				0.5	0.3
Services				0.8	0.5				1.0	0.6
Labor										
Property										
Transfer HH										
Wage HH										
Rent HH										
Government				0.6	0.4				0.5	0.4
Capital										
Rest of the U.S.										
Rest of the World										
Amount							1	1	1	1

vides information on the intensity of the impacts to each activity and the time taken to recover.

In the base scenario, it is assumed that damage to the various production activities in neighboring counties Tipton and Fayette (in Tennessee), Crittenden and Mississippi (in Arkansas), De Soto and Marshall (in Mississippi), is proportionately the same as in Shelby County. The scenario provides an assessment of the "status quo" response of the Memphis area economy to a disruption of electricity supply. The total economic impact on each activity is determined as the short-term (direct) curtailment of its activities, plus the subsequent indirect loss arising from downstream effects as the initial disturbance begins to affect the entire regional economy.

The results are shown in the graphs of Figure 8.3. The first set of graphs show the direct effects spread over roughly the same time-frame as in Chapters 6 and 7, with the shut-down beginning in late-1994 and extending into 1995. The graphs on the following page show the total impacts when indirect effects, and spillover into adjacent counties and regions are taken into account. Within Shelby County, the indirect effects on production and households are comparable in size to the direct impacts. Moreover, because of transaction lags, the indirect effects continue to be felt well after the initial (direct) production losses have been restored.

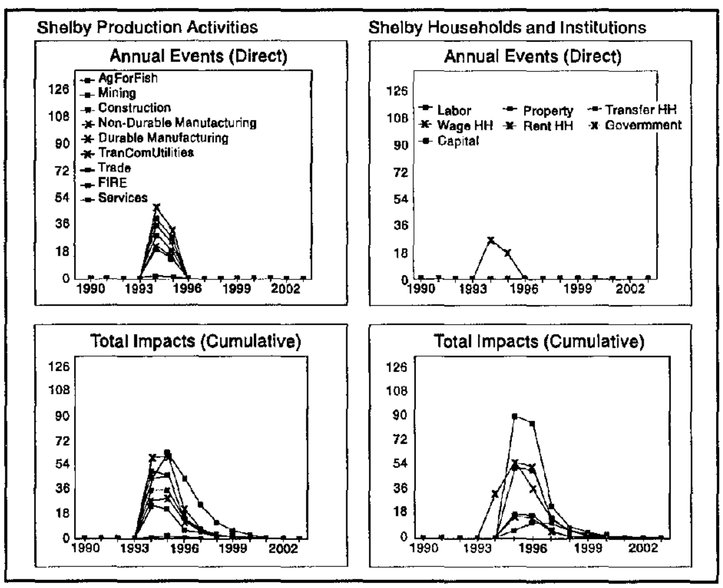


Figure 8.3 Direct and Indirect Consequences of a Power Cutback (Base Scenario)

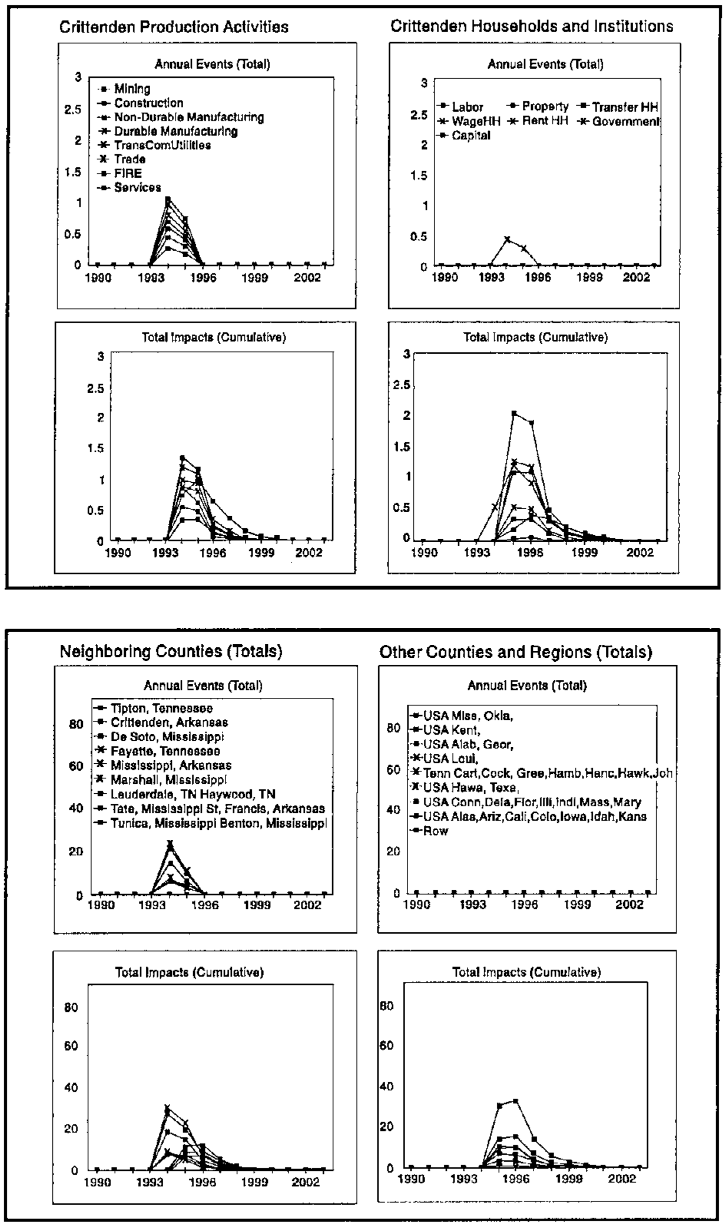


Figure 8.3 Direct and Indirect Consequences of a Power Cutback (Base Scenario) (continued)

Table 8.5 Base Scenario and Optimal Impacts by Locality and Activity

Shelby, TN												
			Non-optimal				Optimal				Ratio Optimal/ Non-Optimal	Ratio Optimal/ Growth
Sector	Annual Output	Annual Growth	Direct Loss	Share Annual	Total Loss	Share Annual	Direct Loss	Share Annual	Total Loss	Share Annual		
						1				1		
Agriculture, Forestry, Fishing	773	7%	2.7	0.4%	6	0.8%	2.7	0.3%	6	0.7%	93%	10%
Mining	29	-4%	0.7	2.3%	1	4.8%	0.8	2.7%	1	4.9%	102%	-122%
Construction	3546	1%	39.7	1.1%	66	1.9%	2.0	0.1%	17	0.5%	26%	52%
Nondurable Manufacturing	3724	4%	99.0	2.7%	154	4.1%	119.1	3.2%	159	4.3%	104%	106%
Durable Manufacturing	3935	1%	44.9	1.1%	79	2.0%	3.4	0.1%	19	0.5%	24%	44%
Transportation, Communication, Utilities	7857	5%	72.7	0.9%	117	1.5%	89.7	1.1%	121	1.5%	103%	31%
Trade	6372	2%	83.1	1.3%	124	1.9%	97.1	1.5%	120	1.9%	97%	110%
F.I.R.E.	5709	2%	59.8	1.0%	97	1.7%	2.4	0.0%	25	0.4%	25%	21%
Services	12125	2%	73.5	0.6%	197	1.6%	2.9	0.0%	69	0.6%	35%	25%
Labor	14729	2%			217	1.5%			127	0.9%	59%	38%
Property	6931	4%			128	1.8%			78	1.1%	61%	26%
Transfer HH	2758	6%			41	1.5%			17	0.6%	42%	11%
Wage HH	11180	3%			134	1.2%			79	0.7%	59%	25%
Rent HH	3408	4%			37	1.1%			23	0.7%	61%	16%
Government	8608	4%	53.9	0.6%	148	1.7%	1.5	0.0%	62	0.7%	42%	20%
Capital	3839	2%			42	1.1%			25	0.7%	61%	29%

Crittenden, AR												
Sector	Annual Output	Annual Growth	Non-optimal				Optimal				Ratio Optimal/ Non-Optimal	Ratio Optimal/ Growth
			Direct Loss	Share Annual	Total Loss	Share Annual	Direct Loss	Share Annual	Total Loss	Share Annual		
						1				1		
Agriculture, Forestry, Fishing	65	8%	0.2	0.4%	0.6	0.9%	0.2	0.3%	0.5	0.7%	84%	10%
Mining	62	-5%	1.5	2.3%	1.6	2.6%	0.0	0.0%	0.1	0.2%	8%	-5%
Construction	53	3%	0.6	1.1%	1.1	2.1%	0.6	1.1%	1.0	1.8%	86%	65%
Nondurable Manufacturing	86	2%	2.3	2.7%	2.9	3.4%	1.8	2.1%	2.3	2.7%	79%	141%
Durable Manufacturing	130	1%	1.5	1.1%	2.2	1.7%	1.6	1.2%	2.0	1.5%	92%	105%
Transportation, Communication, Utilities	181	6%	1.7	0.9%	2.5	1.4%	1.8	1.0%	2.4	1.3%	97%	21%
Trade	156	3%	2.0	1.3%	2.9	1.9%	1.6	1.0%	2.3	1.5%	78%	46%
F.I.R.E.	91	5%	1.0	1.0%	1.3	1.5%	0.9	0.9%	1.1	1.2%	83%	24%
Services	214	6%	1.3	0.6%	3.2	1.5%	1.6	0.8%	3.0	1.4%	96%	23%
Labor	322	3%			5.0	1.5%			4.3	1.3%	87%	48%
Property	479	3%			2.9	0.6%			2.4	0.5%	84%	18%
Transfer HH	220	6%			1.5	0.7%			1.3	0.6%	82%	9%
Wage HH	256	4%			3.1	1.2%			2.5	1.0%	79%	26%
Rent HH	161	6%			1.4	0.9%			1.1	0.7%	78%	11%
Government	147	3%	0.9	0.6%	3.5	2.4%	0.9	0.6%	3.0	2.0%	85%	65%
Capital	110	3%			1.0	0.9%			0.8	0.7%	79%	25%

8.5.3 Income Distribution and Interregional Impacts

Table 8.5 shows the total impacts for all activities — businesses, factors, institutions, households and government — in the Shelby and Crittenden counties accumulated to the year 2005. It is seen that, even though the two economies experience proportionately the same initial shocks, the total impact, after all multiplier effects are accounted for, differ markedly. With the mining sector, for example, the initial shock in both counties is 2.3% of annual output,.but rises to 4.8% in Shelby, but only 2.6% in the smaller Crittenden economy. The loss of household income to households in Crittenden is also somewhat less than in Shelby, partly because of the differences in size and structure of the two economies, and because of the pattern of commuting between them. The table also shows that the loss in wage income to workers is somewhat less than the loss in net profits to businesses. This pattern is not fully reflected in the shares of income loss by wage and rent to households because a considerable portion of rent and transfer income comes from well outside the Shelby area (via investments, retirement funds, and state and federal government), and this cushions the local impact.

The consolidated impacts for each county and regional bloc are shown in Table 8.6. It is seen that in absolute terms there is considerable spill over into neighboring counties, and even to distant regions of the United States. While this is not a "disaster" (it is indeed relatively insignificant) for these distant regions, it still implies a considerable loss to the nation as a whole (as large as the loss to Shelby County itself). Arguably, this spill over effect should be taken into consideration in any cost-benefit of disaster preparedness measures. This is not least because the spillover from a large county such as Shelby onto its smaller immediate neighbors can also be comparable to the impacts of events within the small county.

This base scenario illustrates some implications of the Memphis model for income distribution, and inter-county phenomena. In practice, these impacts would be considered in the context of other events, for example, the failure of water supply and transportation lifelines also caused by the earthquake, as well as the appropriate policy responses (such as federal aid to victims).

Table 8.6 Direct and Total Impacts by Locality and Region (all dollar figures in millions)

Sector/Locality	Total Output	Direct Loss	Share of Output	Total Loss	Share of Output
Shelby TN	$95,524	$529.9	0.6%	$1,634.0	1.7%
Tipton TN	2,228	12.4	0.6%	26.8	1.2%
Crittenden AR	3,332	25.9	0.8%	55.3	1.7%
De Soto MS	4,900	38.1	0.8%	84.1	1.7%
Fayette TN	1,550	12.0	0.8%	23.5	1.5%
Mississippi AR	5,469	42.5	0.8%	89.1	1.6%
Marshall MS	1,336	10.4	0.8%	19.2	1.4%
Lauderdale TN/ Haywood TN	1,036,470			123.4	0.01%
Tate MS/St. Francis AR	218,678			74.2	0.03%
Tunica MS/Benton MS	160,787			58.7	0.04%
MS, OK	677,824			69.6	0.01%
Kent KY	250,730			30.6	0.01%
AL, GA	839,169			71.4	0.01%
LA	587,638			32.5	0.01%
TN (Cart., Cock., Gree., Hamb.)	1,986,166			7.4	0.00%
HI, TX	1,204,215			95.5	0.01%
CT, DE, FL, IL, IN	9,462,701			346.1	0.00%
AK, AZ, CA, CO, IA	10,583,205			159.7	0.00%
Total USA	27,121,921	671.1	0.0%	3,001.1	0.01%

Note: Total output is income of all activities

8.5.4 Reallocation of Resources

Depending on the precise details of the local lifeline system, there will always be some discretion exercised as to which parts of the power network will be repaired first, or how the available capacity will be allocated. The model may be used to illustrate how different priorities with respect to the allocation of supply might reduce the cost of a disaster to the community as a whole, and how this will affect specific communities and industries (see Cole, 1995). With this Memphis example, there is the possibility, for example, of re-directing the remaining electricity supply, or reinstating supply in such a way as to reduce the overall economic losses to the wider community as in Chapter 7. Such optimal reallocation of supplies is also possible with the multi-region social accounts (see Cole, 1995).

Table 8.5 compares the results of an optimal allocation with the base (non-optimal) allocation described above for Shelby and Crittenden counties. For the alternative scenario, the total shortfall in (the value of) electricity supplied to Shelby and Crittenden counties over the period of the cutbacks is reallocated so as to minimize total accumulated loss in value added (Gross Regional

Product) to the region. To achieve this, the reallocation reduces cutbacks to sectors which have a high total (direct plus indirect) income loss for a given total power loss. In this example, all activities are constrained not to expand production above their pre-disaster level. Without going into detail, it is clear that there are some considerable reductions in the overall impact compared to the base scenario. There are also substantial shifts in the direct and indirect losses for the various production activities and institutions, which may be traced to their varying composition of inputs (especially electricity). For a given activity, these shifts are sometimes in different directions between the two counties. For example, the direct loss to nondurable manufacturing increases from $99 to $119 million in Shelby, but reduces from $2.3 to $1.8 million in Crittenden. Thus, the reallocation has quite different implications for industries in the two counties. It also has different consequences for households so that the losses to households in Shelby are reduced to about 50% from base scenario, while losses in Crittenden are reduced only by 20%.

8.6 INTEGRATION INTO POLICY MAKING

These calculations illustrate a number of important points about policy-oriented models. Not least is that, while significant overall savings are possible, economic factors are likely to be impacted unevenly. Even a fairly innocuous goal such as reducing losses to community-wide value added is not in the interests of all individual industries or communities. From a policy perspective, the last conclusion emphasizes that strategies chosen to deal with any untoward and disastrous incident is inevitably a matter of negotiation between the affected parties. In the example used in this chapter, an overarching question is, if the community loses a given amount of electricity supply how might the cutbacks be distributed in order to minimize the ensuing impacts to selected interests in a mutually acceptable manner? The aim is to provide a "cost-benefit" analysis that can deal with the tradeoffs between economic and non-economic welfare, and the competing needs of various interest groups and communities (see e.g., Layard, 1980).

Certainly, it is important to consider a range of alternative recovery strategies, responses, and scenarios, so that critical tradeoffs and choices for different interest groups can be identified, and so facilitate negotiated compromises. Ideally, interests should be weighted to establish some broadly acceptable allocation, recognizing that there are several difficulties in balancing economic and non-economic utilities across competing interest groups. It is argued in Cole (1995) that most contingency evaluation should be treated as a multi-criteria assessment rather than a cost-benefit analysis (van der Veen et al., 1994). It should be said that while economists have devised these methods to assess the imponderables associated with more sustained environmental hazards, these methods may be less useful for the situation of sudden disasters. Sudden disasters present some major problems because of their uniqueness, the difficulty in assembling data, the complexity of the institutions, the modus operandi of actors involved in negotiation, and so on. For this reason, it is necessary to consider how models such as those described in this chapter might be employed to best effect.

8.6.1 Decision Support Systems versus Expert Systems

The way in which the social accounting model and the event matrix might be used to aid decisions depends on the precise application. To explore this, it is useful to distinguish between two types of application in "well defined" and "poorly defined" or "chaotic" situations.

The first application approximates the circumstances of Memphis as a research laboratory for disaster preparedness. The second corresponds to the type of situation for which the modeling system developed here ultimately is designed to contribute. These distinctions dictate the type of modeling system that might be usefully employed, emphasize the balance between quantitative and qualitative representation, and the degree to which problems are well, or ill-defined, and thus the extent to which they can be modeled in a mechanical fashion (see, e.g., Harris and Batty, 1993; Choi and Kim, 1992). It should be said that the promise of expert systems based on concepts of artificial intelligence has proved hard to realize and, even for well defined situations, the literature increasingly speaks of decision support systems rather than expert systems (Guariso and Werthner, 1991). While the approach of this project falls into the generally accepted definition of aiming to help a community do for itself what otherwise experts might be asked to do (see, e.g., Borri, et al., 1994), this nevertheless leaves open many issues of system interface design and mode of application.

The two types of application — well-defined and chaotic — also map closely onto the distinction made in other investigative sciences such as anthropology between the *emic* and the *etic* perspectives (i.e. the local views of a community versus the outside analysis of the development agencies or researchers). As Dyer (1995) and others have argued the "culture of response" is derived from the intersection of these perspectives, and this is critical for determining the overall outcomes of the recovery process. The internal process is dictated by the immediate felt needs and shared cultural values of the impacted community, while the external response comes from any outside agencies (such as the Federal Emergency Management Agency) that are mandated to mitigate the effects of a disaster.[5]

In chaotic situations, there is much evidence that very sophisticated models are quite unacceptable in some policy making situations (United Nations, 1994). This second type of situation therefore appears to demand a reduced decision support system — one that is quite open to public scrutiny and modification. Thus, even though the manner in which the model is derived may be fairly sophisticated, it must have the ring of truth about it for the local community. To be effective, it must be possible for local groups to be highly involved, and to see that their interests are accounted for properly. Such lessons are clear from the work of authors such as Cuny (1983), Pantelic (1989), and Dynes and Tierney (1994). The challenge remains to bring the more elaborate but (hopefully) better-specified models such as those described here out of the research mode and transform them into effective aids for disaster preparedness and recovery, and fulfill the hope long expressed by Jones (1981, 1989), Aysan et al., (1989), and others, that natural disasters, however painful, can be used to stimulate positive developments in the community.

NOTES

1. This provides the basis for later transforming into social categories of households who are most at risk from disasters. For example, in the pilot studies mentioned earlier, households have been sub-divided, by minority status, gender, and age (Cole, 1994), and by residence and kinship networks (Cole, 1993; Cole, 1996b).

2. The procedures are developed in Visual Basic for Excel (see Cole, 1997).

3. In Cole (1988) it is shown that a general approximation to solution of the calculation of time-lagged economic impacts is given by the modified Leontief inverse. For the linear case (i.e. a diagonal transaction matrix), this reduces to the Shinozuka et al. (1995) fragility equation used in Rose et al. (1997, and Chapter 7 of this monograph), and Bates' (1994) method for analysis of travel time reliability. The manner in which the equation might be adapted to the situation when an economy collapses progressively as a consequence of a very large disturbance, and the properties of the solution when clusters of counties are aggregated together, are discussed in Cole (1997).

4. A similar method has been proposed by Boisvert (1992).

5. The manner in which these interact is still a matter of debate. Oliver-Smith (1995), for example, notes that neither rational choice theory, nor the resource mobilization approach, both of which underlie the research model developed here, can account for the social and emotional conditions following a disaster.

Implications for Effective Lifeline Risk Reduction Policy Formulation and Implementation

9

by Laurie A. Johnson and
Ronald T. Eguchi

Reducing the potential loss of property and lives, or the risk, of future damaging events, is the primary motivation for most earthquake hazards research. Resulting risk reduction policies and actions are also the principal measures of effectiveness for research programs, products and practices (Nigg, 1988). Unfortunately, as succinct as the objectives for effective earthquake risk reduction may seem, the process leading from scientific innovation to risk reduction policy formulation and implementation is extraordinarily complex.

Petak (1993) defines risk management as "concerned with the actions necessary to mitigate or control the risk" and that these actions "derive from a decision process that results in the policies that establish a level of acceptable risk for the community or organization." Clarke (1989) defines the process of determining the level of acceptable risk as having five key steps: "defining the problem, assessing the consequences, ordering the alternatives, constructing acceptable risk assessments, and accepting the risk" (including implementing measures to achieve the acceptable level). Therefore, acceptable risk is as much a political issue as it is a scientific issue.

To many in the research field, earthquake knowledge generation is described with terms like "scientific breakthrough" and "product development" — those milestones leading to advances in the state-of-knowledge. These efforts often focus on advancing aspects of risk analysis (e.g. hazard characterization, vulnerability analyses, and risk assessment). But, comprehensive risk management must include more than risk analysis and knowledge generation in order to affect change, or, in this case, influence risk reduction policymaking (Petak, 1993). It must also include knowledge development to apply effective risk reduction practices (e.g.

technology transfer, education, and training) as well as empowerment to formulate, adopt, implement and sustain practices and policies that make our communities safer from earthquakes (Cassaro et al., 1995; CUSEC, 1993).

In the area of lifeline earthquake risk reduction, recent discussions within the Technical Council on Lifeline Earthquake Engineering (TCLEE) of the American Society of Civil Engineers (ASCE) have suggested that the gap between the lifelines technical and policymaking communities is significantly greater than many other areas of the earthquake community (Taylor, 1996). Therefore, investigators in this study have been handed an even greater challenge, and likewise a greater opportunity, to envision the bridge that leads from innovation to policy implementation.

This chapter attempts to help build this bridge by focusing on the policy implications of the engineering and socioeconomic analyses of earthquake-induced electric power disruption in Memphis, particularly as they relate to earthquake risk reduction for lifelines systems. In the first part of this chapter, some of the significant additions to the existing knowledge base for lifeline risk reduction, resulting from this study, are examined. They are:

- Substantial advances in accessing the indirect losses on affected service users for consideration in future performance design criteria for electric power systems.
- Advances in assessing optimum strategies for service restoration following a major disaster.
- Advances in defining the resiliency factors to estimate economic losses over time.

In the second half of the chapter, beyond the knowledge advances resulting from this study, the problem definition, potential solutions, participants, opportunities for choice, and institutional capacities that may lead to better lifeline risk reduction policies and actions in the central U.S. and beyond are considered.

9.1

STUDY IMPLICATIONS

1. Substantial advances in assessing the indirect losses on affected service users for consideration in future performance design criteria for electric power systems.

The performance of electric power systems is generally measured by the repair costs resulting from actual disasters. In these measurements, the indirect losses, associated with factors such as utility outages, outage time, or the effects on dependent businesses are largely ignored. This is primarily due to the lack of statistical data or actuarial experience to quantify these impacts. The methods outlined in this report provide a way of simulating these impacts. Whether or not these measurements or methods can be reasonably implemented by the electric utility industry and public officials responsible for disaster management is not yet certain.

In order to understand the significance of indirect losses in measuring the performance of electric power systems, several comparisons are made in Table 9.1. This table reproduces the results of the direct and indirect loss calculations made in Chapter 7. In addition, information on the estimated repair costs to the Memphis Light, Gas, and Water (MLGW) electric power system in the same New Madrid earthquake scenario have been added using data from a related NCEER report (Chang et. al., 1996).

The total repair cost shown in Table 9.1 was derived from data produced by Chang et al. (1996). This report also uses a M 7.5 earthquake near Marked Tree, Arkansas to simulate the effects on the MLGW electric power system. In addition to electric power, this study also investigated the impact on water and natural gas distribution systems. The results of the Chang report indicate that repair costs to major substations in a large New Madrid earthquake could be as high as $400 million. Most of this damage would occur in major gate stations ($366.5 million or roughly 91% of the total repair cost). Additional damage would occur to lower voltage (23 kv and 12 kv) substations — approximately $35 million.[1]

The direct and indirect economic losses as computed in Table 9.1 were taken from Table 7.2. Direct losses were interpreted as

■ Table 9.1 Repair Costs and Associated Direct and Indirect Economic Losses Due to the Failure and Disruption of Electric Power Service in a Large New Madrid Earthquake

Industry Sector By SIC Code	Baseline Gross Output (mil $)	Estimated Repair Costs (mil $)	Post-EQ Direct Losses - Gross Output Terms (mil $)	Post-EQ Indirect Losses - Gross Output Terms (mil $)
Agriculture	203		4	14
Mining	40		1	3
Construction	2,456		46	165
Mfg.	9,174		263	526
T.C.U.	4,930		79	344
Wholesale	2,140		39	145
Retail	2,911		53	198
F.I.R.E.	3,941		95	243
Services	5,477		125	346
Government	3,229		82	196
Total	34,501	401[a]	787	2,180

[a]Estimated repair costs taken from Chang et al., 1996.

those associated with gross output losses that consider no bottleneck effect. In other words, each economic sector is assumed to be impacted only by a disruption of electric power service and not additionally by supply input bottlenecks from other sectors. Indirect losses are then calculated by subtracting these "non-bottleneck" losses from those gross output losses that do account for bottleneck effects. These indirect losses model the so called "multiplier" or "ripple" effects.

As Chapter 6 (Direct Economic Impacts) points out, calculating indirect losses can be difficult, partly caused by the many assumptions required to execute the methodology. Resiliency or importance factors are needed, for example, in order to quantify the dependencies businesses have on electric power service. As Chapter 5 (Socioeconomic Analysis of Lifeline Usage) notes, these dependencies can vary widely depending on the type and size of the business. Future studies should focus on the sensitivity of indirect losses on changes in input parameters and assumptions.

A comparison of the various losses in Table 9.1 shows that indirect losses are approximately five times larger than expected repair costs and about 2.5 times larger than direct losses. More importantly, the combined total of direct and indirect losses are about seven times larger than expected repair costs. This ratio is significant since, in most earthquakes, the only economic loss data generally reported by electric power utility companies are the total repair costs. Therefore, the full economic impact of electric power failure and disruption is, in general, grossly understated. In fact, accounting for regional losses (i.e., beyond Shelby County) would add to the totals given in Table 9.1 (see discussion of metropolitan losses in Chapter 8), thus increasing the total impact of the earthquake well beyond repair costs.

Chapter 8 essentially expands spatially and temporally much of the analysis in Chapter 7. The decision support system comprises several components:

- Social Accounting Matrices for the Memphis metropolitan area counties as well as the U.S. as a whole. This allows for the analysis of impacts upon various segments of society, especially different income classes and racial/ethnic groups.
- A GIS overlay system so that the county-level data can be reconfigured to any geographic area.
- A set of impact algorithms that can determine the indirect impacts from an earthquake both spatially and temporally, i.e., for any county grouping and to include lags and impacts (other models to date typically assume all impacts take place within a fixed time period, most typically a year). Also, this lag structure can be applied to the pace of recovery.
- An optimization routine that allows for the specification of alternative objective functions for minimizing losses through the reallocation of scarce resources (e.g., it allows for differential weighting of various stakeholders). This framework is more general than that of Chapter 7 in terms of the number of objectives, but not as detailed in terms of factoring in lifeline system considerations.

The terminology in Chapter 8 of a "decision support system" approach is for sophisticated users and allows for the maximum flexibility and range of outputs. It is intended as an aid to decision-making and not a substitute. It emphasizes the use of professional judgement in specifying model objectives, data and policies. This is in contrast with an "expert system," which is usually quite rigid and intended to provide the answer.

2. Advances in assessing optimum strategies for service restoration and allocation following a major disaster.

Chapter 7 provides some insights into how the procedures developed in this study could be used to optimally ration scarce electricity after a disaster, and to determine more effective restoration patterns or strategies. The results show that indirect losses can be reduced three-fold if scarce electricity is reallocated according to a specially designed linear programming model, and four-fold if an optimizing algorithm is employed for determining the best sequence for bringing back on-line damaged substations. As stated earlier in this section, whether these algorithms can be effectively incorporated within the framework of an existing electric power utility's program is another issue. The fact that these algorithms have a significant effect in reducing potential losses to dependent businesses, however, should provide enough impetus for policymakers to at least explore the merit of using these methods in post-disaster applications.

At the end of Chapter 7, several methods for implementing these algorithms were introduced. One method of rationing proposes that electric power utilities could establish a contingent contract with customers, whereby the availability of service after a major earthquake would be tied to a premium and usage fee. By negotiating before the event, customers would agree to the fee they would pay for priority service after an earthquake. In implementing such a policy and program, utilities could maximize their capacity to provide service to the larger area or region. Other forms of rationing could include "rolling blackouts," that allow customers to share residual power in the service region, and other pricing structures that charge higher fees for greater usages.

It is unclear how such rationing strategies might work to distribute power after a major earthquake. These rationing methods presume that the power distribution system will remain intact to carry electricity to customers, which contradicts the system vulnerabilities underscored by recent earthquakes. Transmission and distribution substations have historically been the weak link in power distribution. Therefore, any optimization algorithm for allocating residual power needs to consider additional scenarios with certain key components missing.

3. Advances in defining the resiliency factors to estimate economic losses over time.

Chapter 5 summarizes the results of an extensive survey of Memphis businesses and it substantially advances our understanding of business dependencies on utility services. The resulting data provides important information which can be used to calibrate resiliency[2] factors that are largely based on expert opinion (ATC-25, 1991). As currently defined, these factors lack: 1) the ability to model specific lifeline dependencies within a region, 2) the ability to recognize the recovery time path after a disaster, and 3) the spatial dimension of lifeline service disruption and economic impact.

In this study, indirect loss analyses have been expanded by developing resiliency factors which account for the three attributes identified above. These new factors allow a more explicit definition of lifeline dependency by quantifying the length of time a business can operate without utility service. This information can be important to businesses in general by defining the minimum requirements for continued operations. If this data are known, and if some assessment of utility outage can be provided, then businesses can develop individual emergency response plans that offer alternatives for dealing with utility company service disruptions. Chapter 6 discusses the potential benefits of this type of planning.

With the application of these new resiliency factors in Memphis, efforts to enhance this kind of information in other parts of the country may be more likely. This study illustrates the significance of incorporating local data about business dependencies into loss estimates. It is particularly important for agriculture, mining, construction and transportation, communications and utility industries. Therefore, any effort to improve the reliability of this data would be meaningful.

9.2 Towards Effective Lifeline Risk Reduction Policy Formulation and Implementation

Based on interviews with representatives of six major utilities, Taylor (1996) notes two significant barriers to lifeline risk reduction policy implementation as: 1) the importance of private utilities, and the comparative lack of reasons for federal interest in the seismic performance of these utilities; and, 2) the multi-jurisdictional nature of lifeline networks, involving local, regional, state, and federal jurisdictions. In contrast, seismic building codes, retrofit programs, and land use plans are typically adopted by only one jurisdiction. But in spite of the many constraints challenging lifeline risk reduction policymaking, successful policies and practices have been implemented.

The second half of this chapter synthesizes significant aspects of public policy research in with anecdotal insights gained from current lifelines industry practices as an opportunity for formulating and implementing more effective lifelines risk reduction policies and practices in the central U.S. and beyond.

9.2.1 Policy Formulation Model

An organization decisionmaking model, referred to as the "garbage can model of organizational choice" has been adopted by several hazards researchers to describe the public policy formulation process. As Petak (1993) notes, the garbage can name derives from the recognition that "decisionmakers are frequently confronted with numerous simple and complex problems, multiple solution alternatives and choice opportunities." Therefore, under this model, four essential ingredients that must exist in order for decisions or policies to be made are problems, solutions, participants, and an opportunity. Mittler (1989) suggests that a fifth ingredient — institutional capacity — must also exist in order for policy to reach the issue agenda and be adopted. The following sections consider how these five ingredients mixed with knowledge advances resulting from this study can lead to more effective lifelines risk reduction policies and practices.

1. Achieving an appropriate risk reduction policy requires a clear and precise explanation of the problems being considered.

Earthquake risk estimation provides helpful information for developing a greater understanding of the expected losses, and therefore establishes a frame of reference in which policymakers can weigh specific risks (Petak, 1993). This study enhances the understanding of two important problems: 1) improving the understanding of the seismic risk in the central U.S., and 2) illustrating potential deficiencies in current seismic performance design criteria for electric power systems.

While the probability of a large central U.S. earthquake continues to be a subject for scientific controversy and debate, the potentially overwhelming economic impacts (both regionally and nationally) can not be ignored. To an experienced utility operator or engineer, the information in this study is probably at best, provocative food for thought. Utility companies should not be expected to make a decision to review their acceptable risk policies or to implement a risk reduction action based on this information alone. However, this study provides compelling evidence for considering a long-term risk management strategy to reduce the earthquake vulnerability of Memphis' electric power system, and appropriate next steps might be to consider the consequences of additional earthquake scenarios.

The relative loss data in Table 9.1 may also be useful for utilities, in defining earthquake risk reduction policy, by establishing more appropriate and acceptable performance criteria for electric power systems. A number of recent technical documents (including the *FEMA/NIST Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines*) underscore the importance of examining lifeline performance from a broader range of impacts, beyond repair costs.

On a relative scale, repair costs (as indicated by Table 9.1) account for a small percentage of the economic impacts associated with the failure and disruption of electric power systems. If an assessment of acceptable performance is based solely on these costs, then earthquake risk reduction measures may overly emphasize seismic design criteria for critical equipment and could ignore opportunities to improve operational procedures that may also account for large reductions in potential losses to affected users. A more detailed analysis of the indirect effects could provide an added impetus to electric power utilities and regulating agencies to explore other measures for reducing expected downtimes and/or improving restoration efforts.

2. Viable solutions are needed to translate policies on acceptable levels of earthquake risk into meaningful risk management strategies with specific actions, milestones, and budgets.

Generally speaking, mitigation involves programs or activities that will: 1) reduce the probability and/or intensity of an event, 2) reduce the vulnerability of structures, contents and process systems to the forces caused by an event, and/or 3) reduce the exposure of people and property to an event (Petak, 1993). The loss estimation methodologies utilized in this study, relied on local information on businesses and the economy to calibrate business resiliency to lifeline disruption and to identify the pattern of economic activity at risk throughout Shelby County. A number of viable solutions for loss reduction policy formulation, including post-disaster recovery strategies and pre-disaster planning, have also been proposed.

This study provides a number of operational strategies which might reduce potential losses to customers. These strategies are based on innovative techniques to optimally allocate limited post-earthquake service capacities or improve restoration times to more economically important businesses. The self rationing alternative suggests that customers pay a non-interruptibility premium, to ensure a certain level of capacity before the earthquake, and, if possible, in its aftermath. This allows the utility to optimize resource allocations by setting usage prices and also to guarantee enough capacity to manage the systems' load. The direct quantity rationing alternative proposes using rolling blackouts for non-essential industries or similar means to directly control the temporal and spatial distribution of power restoration.

A more effective restoration scheme, based on economic factors, provides many opportunities for reducing both the short- and long-term losses caused by earthquake-damaged electric power systems. Studies have shown that long-term recovery can be enhanced if the right set of decisions are made in the early stages of an earthquake disaster. Many businesses can operate for short periods of time without electric power service, however, extended outages can lead to business failures and closures. Using these models, utilities have an opportunity to join with other agencies in establishing restoration priorities, and therefore provide a more coordinated, multi-agency recovery effort. For small communities, this is a straightforward task, particularly where one business is responsible for the region's primary economy. For larger urban areas, however, this may be more difficult and would require a more sophisticated approach.

In addition to electric power utilities and affected business owners, insurance companies might also be interested in the resulting methods to quantify indirect losses. There may be a market demand for insurance riders that cover business interruption losses, resulting from direct damage to the facility or building, or external factors, such as loss of electric power service. This coverage is not generally offered because of the lacking actuarial experience to assess risk and appropriate premiums. The methods developed in this study could be used to calculate the potential magnitude of these losses and then used in establishing a credible insurance structure. As a result, insurance companies might be better able to offer business interruption coverage on a broader and less restrictive basis.

3. Identifying and mobilizing internal "champions" for earthquake risk reduction is essential for policy formulation and implementation.

Broadly speaking, effective earthquake risk reduction requires the participation of scientists, engineers, and policy makers (Nigg, 1988; Petak, 1993). More specifically, in lifeline earthquake risk reduction, a highly diverse and specialized group of lifelines and systems research engineers, engineering seismologists, utility owners and operators, facilities engineers and managers, emergency managers, regulators, insurers, and government officials, are essential.

Furthermore, recent studies have illustrated the value of viewing research utilization not as a linear process in which knowledge producers simply inform users (Michaels, 1992; Cassaro et al., 1995; Taylor, 1996), but rather, as a more iterative and interactive process, involving "information networks" with diverse groups of participants having similar concerns.

With regard to this study, some particularly relevant target networks are TCLEE and the Earthquake Engineering Research Institute (EERI) for lifeline engineering design and construction professionals, electric power industry associations for utility owners and operators, and insurance associations for risk managers of key insurance companies. The following section identifies some of the current federal, multi-state and regional initiatives which offer key opportunities for influencing existing risk reduction policy networks in the central U.S.

Finally, with regard to advocacy concerns, the Memphis business survey data described in Chapter 5 suggest that "the current approach to encouraging earthquake and general disaster preparedness among businesses, which emphasizes public awareness and education, is achieving little." The chapter also suggests that in order to achieve more widespread adoption of loss reduction measures, new policy implementation strategies must make such measures attractive to and affordable for the business community.

4. Good people, with good solutions to clearly defined problems, may be able to formulate effective risk reduction policies. Policy adoption, however, can not occur without an opportunity for political choice or action.

According to Taylor (1996), landmark seismic evaluation programs have been instrumental in placing earthquake issues on the utility companies agendas. Furthermore, a key influencing feature of the lifeline success stories is the place lifeline earthquake risk issues typically hold as "standing issues" (not always pressing but always present) on the political agendas of utility companies and other policymakers. In a sense, they are part of the constant attention paid to lifelines by policymakers. In contrast, many other seismic issues have difficulty getting on the agenda at all, or of gaining the attention of policymakers. Based on these insights, the window of opportunity for lifeline seismic risk reduction may be more widely and consistently opened, than it might be in other parts of the earthquake community. Some potential opportunities relevant to this study include:

- ***Individual companies***. In 1994 and 1995, the Central U.S. Earthquake Consortium, with support from the Department of Energy, developed and conducted a technical, hands-on two year program for senior electric utility managers in the seven CUSEC states. As participants in the program, each utility carried out a vulnerability assessment of their respective facilities and systems, developed a utility policy on acceptable levels of risk, and developed a mitigation plan and implementation strategy for their utility (Palmer and Shaifer, 1995).

- ***Industry sector initiative.*** The Tennessee Valley Public Power Association (TVPPA) represents electric utility distributors in the Tennessee Valley Authority regions. TVPPA has developed a Model Emergency Response Plan for Utilities and has conducted relevant training sessions and workshops in emergency planning, training, and information exchange for electric utilities in the regions. Participants at the 1995 Annual Meeting of the Central U.S. Earthquake Consortium (CUSEC, 1995) recommended that the Department of Energy, CUSEC and TVPPA collaborate to develop and implement a comprehensive emergency preparedness program with practical, cost-effective steps for federal, state, local, and utility officials to take to address predictable post-disaster problems and expedite service restoration. Restoration optimization strategies resulting from this study could be particularly useful to this effort.
- ***Multi-state, multi-industry initiatives.*** Two multi-industry initiatives are noteworthy. The first is located in the central U.S. and the second in California.
    a. The Central U.S. Earthquake Consortium is currently in the midst of a three-year program to develop a multi-state, multi-industry strategy for managing and coordinating the large-scale energy emergency response and disaster recovery operations in the aftermath of a catastrophic earthquake in the New Madrid Seismic Zone. A key element of the strategy is the creation of an emergency industry regional support team with designated officials specifically tasked to improve coordination of governmental and energy industry response and recovery operations, as well as to improve support to decision making for priority service restoration and system reconstruction (CUSEC, 1995).

    b. The Inter-utility Seismic Working Group is an ad hoc committee initially formed of earthquake specialists for the major gas and electric power utilities in California, and now including utility representatives from the Pacific Northwest and elsewhere. Group members have collaborated to develop a common policy statement for earthquake vulnerability reduction with the ultimate goal of reaching and maintaining an acceptable level of earthquake risk (Savage, 1995). Each utility is responsible for preparing and implementing a long-term seismic safety plan which complies with the policy statement and is based on current knowledge, technical capabilities and industry practices.

5. For the model to be complete, institutions must also have the necessary resources to formulate, adopt and effectively implement risk reduction policies.

The institutions capable of formulating, adopting, implementing and sustaining the risk reduction practices and policies suggested in this study, must have the necessary knowledge development (e.g. technology transfer, education, and training) as well as empowerment. The investigators involved in this study have taken some important first steps in enhancing knowledge development by involving MLGW staff in the process, and communicating study results in professional journals and at professional meetings and other regional conferences. It is important to recognize, however, that institutional empowerment may not be possible without additional resources, including financial support for workshops and hands-on training. Professional associations, such as TCLEE, ASCE, and EERI, as well as federal and regional agencies, such as the Federal Emergency Management Agency, National Institute of Building Standards, and CUSEC, can play an important role in providing these empowerment resources.

9.3 CONCLUSION

Clearly, the results of this study do not provide a final solution for reducing the economic consequences of a potential New Madrid earthquake. For the first time, however, there is now a more complete listing of the critical models and methodologies needed for taking a more comprehensive view of the potential economic losses resulting from an earthquake-induced, regional electric power disruption. Likewise, there is also a better understanding of how these results might lead to more effective lifeline risk reduction policies and practices.

NOTES

1. As a means of comparison, repair costs to Los Angeles area electric power systems (i.e., the Los Angeles Department of Water and Power and the Southern California Edison Company) during the recent 1994 Northridge earthquake totaled about $180 million. A large portion of this repair cost was derived from damage to nine high-voltage (230kv and 500 kv) substations.

2. Resiliency is defined here as the amount of production capability left after complete disruption of lifeline service. In general, these resiliency factors are specific to particular lifelines and industries. These factors, when compared to the length of time a particular lifeline service is disrupted, can be used to estimate potential business interruption losses.

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CONTRIBUTORS

Dr. Juan Benavides, Professor
Department of Industrial Engineering
Universidad de los Andes
Bogota, Colombia
jbenavid@uniandes.edu.co

Dr. Stephanie E. Chang, Research Assistant Professor
Department of Geography
Box 353550
University of Washington
Seattle, Washington
sec@u.washington.edu

Dr. H. Sam Cole, Professor
Department of Planning
201 D Hayes Hall
University at Buffalo
Buffalo, New York
samcole@acsu.buffalo.edu

Mr. James M. Dahlhamer, Field Director
Disaster Research Center
University of Delaware
Newark, Delaware
dahlhamr@udel.edu

Mr. Ronald T. Eguchi, Vice President
EQE International, Inc.
Center for Advanced Planning and Research
4590 MacArthur Blvd., Suite 400
Newport Beach, California
rte@eqe.com

Dr. Steven P. French, Director
City Planning Program
Georgia Institute of Technology
College of Architecture
Atlanta, Georgia
steve.french@arch.gatech.edu

Dr. Howard H.M. Hwang, Professor
Center for Earthquake Research and Information
University of Memphis
3890 Central Avenue
Memphis, Tennessee
hwang@ceri.memphis.edu

Ms. Laurie A. Johnson, Principal Urban Planner
EQE International, Inc.
Center for Advanced Planning and Research
4590 McArthur Blvd., Suite 400
Newport Beach, California
laj@eqe.com

Dr. Adam Rose, Professor and Head
Department of Energy, Environmental and Mineral Economics
College of Earth and Mineral Sciences
The Pennsylvania State University
University Park, Pennsylvania
azr1@psuvm.psu.edu

Dr. Masanobu Shinozuka, Professor
Fred Champion Chair in Civil Engineering
Department of Civil Engineering
University of Southern California
3620 Vermont Ave. KAP 254
Los Angeles, California
shino@usc.edu

Mr. Philip A. Szczesniak, Regional Economist
Bureau of Economic Analysis Division
U.S. Department of Commerce
Washington, D.C.
philip.szczesniak@bea.doc.gov

Dr. Kathleen J. Tierney, Co-Director
Disaster Research Center
University of Delaware
Newark, Delaware
tierney@udel.edu

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A National Center of Excellence in Advanced Technology Applications

State University of New York at Buffalo
Red Jacket Quadrangle ▪ Buffalo, New York 14261-0025
Phone: 716/645-3391 ▪ Fax: 716/645-3399
E-mail: mceer@acsu.buffalo.edu ▪ WWW Site: http://mceer.buffalo.edu

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