Regional Economic Models for Performance Based Earthquake Engineering

Donghwan An¹; Peter Gordon²; James E. Moore II, A.M.ASCE³; and Harry W. Richardson⁴

Abstract: Regional economic impact models (REIMs) are needed for performance-based earthquake engineering and similar activities. The metropolitan-level performance measures that can be supported by earthquake engineering outputs are fundamentally economic, and regional economic impact models provide the logical link between engineering design decisions and policymaking. How well do REIMs consider the performance of structures (broadly defined to include infrastructure and lifelines) in these facilities’ role of facilitating regional economic performance? We have evaluated 19 REIMs of relatively recent vintage against 11 criteria. These include policy relevance, whether the model reports results for small spatial units, the level of industry disaggregation, the possibility to allow integration of models from various disciplines, whether multiperiod or dynamic analysis is possible, the extent to which key variables (including prices, technology and travel behavior) are endogenous, transferability between regions and countries, operability, accessibility, updatability, and whether applications to earthquakes have been executed.


CE Database subject headings: Economic factors; Models; Socioeconomic data; Earthquake damage; Infrastructure.

Introduction

Over the past decade, earthquake engineering and similar natural hazard based research activities have begun to integrate social science questions into technical research agendas. Consider, for example, the research agenda for the National Science Foundation’s Institute for Civil Infrastructure Systems (ICIS 2002), “interdisciplinary research is ... needed that integrates ... different perspectives, combining, in particular, engineering with the needs of users and communities.” This is trend strongly reinforced by the respective research agendas of the three National Science Foundation Engineering Research Centers that focus on earthquake engineering. The Multidisciplinary Center for Earthquake Engineering Research’s (MCEER 2000) focus on earthquake resilient communities (MCEER 2000), the Pacific Earthquake Engineering Research Center’s (PEER 2002) focus on performance-based earthquake engineering (PBEE), and the Mid America Earthquake Center’s (MAEC 2001) focus on consequence-based engineering are all examples of approaches intended to extend technical knowledge into a social science context, i.e., to a decision making context.

The kinds of socio-economic assessment these strategies entail constitute a broad, heterogeneous area of inquiry involving multiple bodies of knowledge and methodologies. Integrating knowledge in this context is challenging. Economic models are distinct from other tools for socio-economic assessment in that economic models tend to be more quantitative, and are more likely to involve parameterized relationships. Consequently, economic models are often the socio-economic tools best suited to linking engineering and social science research. Further, economic models that include a spatial dimension have a special relevance to earthquake engineering problems.

We contend that regional economic impact modeling has the potential to be the core integrative link between engineering assessment and policymaking. In particular, Regional economic impact modeling (REIM) tools are not optional in the PBEE context. The metropolitan-level performance measures that can be informed by earthquake engineering outputs are fundamentally economic, and regional economic impact models provide the link between engineering design decisions and policymaking.

This note reviews 19 regional economic impact models against 11 criteria that determine the models’ utility for predicting the economic performance of metropolitan and regional economies subject to earthquake damage to structures and infrastructure.

Approaches to Economic Modeling

One of the most important applications of economic analysis is the evaluation of proposed projects and policy measures. Ideally, flows of costs and benefits should be reduced to a single number (net present value or internal rate of return) permitting projects to be ranked and compared (Zerbe and Falit-Baïamont 2002). In
practice, data limitations or controversies over discount rates or other assumptions may make this approach impossible. Public policy decision-making is complex and often beset with noneconomic (but logical) concerns (May 2001). Political interests are likely to see any local job losses as a negative impact and any local job gains as a positive impact, regardless of wider efficiency implications. Efficiency analysis, on the other hand, is more likely to focus on resources conserved.

An interesting, and important, report by NIBS (1994) focused on earthquake loss estimation methodologies including economic losses and social impacts. However, most of these methods are of an ad hoc nature, and do not constitute analytical models. While potentially useful, the approaches involved are very different from each other and from standard economic analyses.

Policy analysis should base recommendations on the fullest reasonable accounting of losses (or losses avoided). A full accounting supposes the ability to trace the full effects of the loss of any facility through the regional economy in spatial and sectoral detail. The most obvious and most widely reported losses consist of damage to stocks, i.e., to physical structures and contents. This perspective does not account for changes in flows. Many important economic losses result from the interruption or diminution of activities and capabilities over time (Rose and Lim 2002). Policy makers are better equipped to make choices if specific impacts on industries and/or communities can be reported.

A REIM is capable of considering the performance of the economic system and how it is impacted by various earthquake policy (mitigation, management, or reconstruction) measures. This survey suggests various criteria by which available regional economic impact models can be evaluated with respect to their capacity to support performance-based earthquake engineering objectives. The fundamental question is: How well do the models consider the performance of structures (broadly defined to include infrastructure and lifelines) in their role of facilitating regional economic performance? Standard economic analysis usually evaluates this performance in terms of changes of income per capita, or employment. In some cases, these changes are reported for individual economic sectors or subregions. Though motivated by PEER's PBEE research activities, the answer to this question also informs the related research activities occurring at MAEC, MCEER, and in any context requiring integration of engineering science and social science approaches.

**Pacific Earthquake Engineering Research Center's Modeling Criteria**

The PEER Center has established a set of modeling criteria by defining a probabilistic foundation for the development of performance-based guidelines, "a generic structure for coordinating, combining and assessing the many considerations implicit in performance-based seismic assessment and design" (Cornell and Krawinkler 2000; Miranda 2000). The general form of this approach calls for assessing the adequacy of a structure's design in terms of a key vector of decision variables, e.g., the mean average frequency of earthquake loss exceeding a given dollar value. According to Cornell and Krawinkler (2000) "...This building/bridge specific loss estimation option..., is very attractive because it permits an evaluation of design (or retrofit) alternatives and provides the owner with the information he/she is most interested in. The question is whether it can be brought to a sufficiently objective level to acquire the confidence of engineers and owners."

In a public policy context, it is important to acquire the confidence of policy makers in addition to that of engineers and owners. Cornell and Krawinkler's loss estimation framework implicitly defines a structural system (a building, bridge, or other infrastructure element) as the system of interest. Unfortunately, this perspective is not sufficient to make earthquake engineering truly policy relevant. The system of interest is neither a component, nor a structure. The system of interest is the entire regional economy. The regional economy is a production system consisting of buildings and residences connected by multiple infrastructure networks. Such a spatially distributed economy has multiple interacting sectors. Production is facilitated by the built environment. Damage to the physical plant associated with any or all of these economic sectors, including labor, will affect the performance of the entire system.

The earthquake engineering literature tends to implicitly equate annual dollar loss to an annualized measure of replacement costs. However, from the broader perspective of benefit-cost analysis and regional economic impact analysis (see, e.g., Richardson et al. 1993; Rose and Lim 2002; Cho et al. 2001), the annual dollar loss associated with damage to a structure has at least five, qualitatively different dimensions, which are possibly confused with definitions of "direct" and "indirect losses" often used in the earthquake engineering literature:

1. replacement costs, what engineers tend to label "direct loss," result from damage to stocks;
2. direct losses due to the lost economic opportunities associated with damage to a building, what engineers tend to label "indirect losses" or "opportunity costs;"
3. indirect losses due to reduced demands for goods and services (other than labor) associated with damage to a building;
4. induced losses due to reduced demands for labor and related reductions in household consumption; and
5. lifeline losses resulting from service constraints due to damage to infrastructure.

In this classification, direct losses are the opportunity cost of lost production in damaged buildings. This loss occurs over a time interval as damaged structures are repaired (or replaced) and returned to economic service. In common economic usage, the phrase "indirect losses" denotes the losses incurred by suppliers as a result of the reductions in demand for inputs normally required by the damaged industries. Induced losses are losses to households due to system-wide reductions in the demand for labor. Direct, indirect, induced, and lifeline losses are all changes in economic flows.

**Model Evaluation Criteria**

The spatial representation of results greatly complicates modeling objectives. It is much simpler to derive results for large geographic units, but political support is usually acquired at the local level, and thus it is important to account for local impacts. This requires models that can present results for smaller geographic units. This requirement must be traded off against limited (and usually less reliable) data available for smaller geographic areas. These limits on the quality and quantity of useful small area data compel analysts to simplify their models. Fifteen of the models assessed here include at least a minimal treatment of space. Of these, only nine offer results at a level of geographic detail smaller than large metropolitan areas. In most cases, these results are only available at the level of counties within metropolitan areas. Four of the models provide results for spatial units below the county level.
To focus our discussion, we have selected 11 criteria (ten plus an information item regarding previous applications of each model) against which to assess the usefulness of 19 REIMs. Some of these criteria combine subcriteria. High scores on many of these subcriteria add up to a good fit between the model of interest and PBEE objectives. The ten criteria fall into two broad categories: Model Structure/Functionality and Model Operationality. We have tried to define criteria that are as separable as possible, but this conflicts with our efforts to select reasonably general criteria, and criteria within these two categories sometimes overlap.

It is tempting to define criteria in entirely terms of mathematical techniques and data requirements, but we have resisted this approach. Instead, we have tried to establish criteria that allow REIMs to be differentiated in terms of both modeling perspectives and procedures.

**Model Structure/Functionality**

**Policy Relevance**

Does the model provide information useful to analyses that support the work of decision makers, policy makers and politicians? The demands on these groups are varied, but impacts on employment levels are usually relevant. Commonly reported dollar magnitudes (lost regional product, output or expenditure) quickly lose their meaning to most people. Moreover, if employment data are available for local political jurisdictions, this probably enhances these data’s policy value. It is also likely that, while disasters can change the course of an area’s long-term growth and development, most policy analysts are most interested in short-term impacts.

**Spatial (Intraregional versus Inter-regional) Dimension**

Most applied economic models apply to the national economy and have no spatial dimension. Others treat subnational units such as groups of states, e.g., the Northeast or the Southwest, single states or counties, and/or large metropolitan areas. A few models go below the metropolitan level and treat smaller spatial units. These could be small cities, communities, traffic analysis zones, census tracts, etc. As noted above, fewer data are available for smaller geographic units, but results for smaller units are more useful to decision makers. Multiregional models are also differentiated insofar as they do or do not explicitly model interactions between the regions represented.

**Interindustry Disaggregation**

Economic models differ in terms of how many economic sectors or industries are explicitly treated. Levels of aggregation vary widely. The whole economy can be described according to a short list of one-digit standard industrial code designations, or by as many as several hundred economic sectors. No matter what the level of sectorization, these models are typically built on assumptions specifying how these sectors interact.

**Integration**

Can the applied economic model easily accept data from other fields, especially earthquake engineering analysis? Can the model easily be used as a step in a sequence of models? Does it include infrastructure systems? Scientific disciplines usually develop somewhat independently of each other: Reconciling their respective, and distinctive, approaches is a serious intellectual challenge. Can the models receive outputs from or provide inputs for models used by the earthquake engineering fields and subfields? Are there solutions (numeric and economic equilibria) that simultaneously respect both engineering and economic changes? This is a key PBEE criterion.

**Dynamic Analysis**

Dynamic models include explicit treatment of time, or apply to more than a single time period. Most economic models are static. These snapshot, equilibrium-seeking or optimum-seeking models are routinely used in sensitivity tests that economists refer to as “comparative statics.” Other models include lagged variables, allowing past values to affect the solution generated for a subsequent period. The most complex models treat time as a continuous variable.

**Degree of Endogeneity**

Are prices, technology choice, and behavior treated exogenously or endogenously? The study of markets is the study of price formation. However, there are several models that include no representations of a price adjustment capability. Leontief’s input–output models and many of the Keynesian-type models pay little attention to prices. Research economists have spent considerable effort adding some degree of price-adjustment capability to these models. The importance of this capability has much to do with the time span under consideration. In the very short run, very little price adjustment takes place. It is likely, therefore, that the capacity to model flexible prices is more important for longer-term reconstruction simulations.

Likewise, although technological choice and change are exogenous in most economic models, considerable effort is now being directed to remedying this situation. Also, models that include the travel choices of individuals or firms often assume that these occur in fixed and predetermined proportions. More realistic models would, of course, allow travel behavior to change as circumstances change.

**Model Operationality**

**Transferability**

Models may be designed with the specifics of a particular region in mind, or they may be easily applied to many places. Regional economic impact modeling tools are often data driven, and thus are often inherently difficult to transfer. Transferability is usually a matter of degree. Modeling approaches can be more easily transferred than individual models. The more modular the model and more use it makes of federal data sources, the more likely it is to be transferable.

**Empirical Viability**

Some models are purely theoretical and are never estimated or calibrated with real data, usually because the data requirements may be too severe. In these cases analysts sometimes rely on synthetic inputs to illustrate the performance of their models. A model that scores low in terms of empirical viability might still be transferable if the results it produces are generalizable. A relationship captured by a model’s outputs might be judged generalizable if the model is accessible enough for this aspect to be investigated.

**Accessibility**

Models may be available in open computer code, and thus can easily be extended or improved by independent researchers. Al-
ternatively, they may be proprietary, in which case users simply manipulate a black box without any substantive understanding of the model's structure. If a model is not accessible, it is difficult to determine whether its results are generalizable.

*Updatability*

In theory, all models are updatable. A model with low empirical operationality may be made more operational if updated with appropriate data. However, even efforts to update operational models often reveal difficulties. For example, complex models often have numerical convergence problems. Achieving convergence for a specific application may depend in part on the quality and scope of base-year data. Attempts to update these data may make convergence more difficult.

**Model Evaluation**

We have evaluated 19 REIMs of relatively recent vintage against these criteria and associated subcriteria. These 19 regional economic impact models are:

1. Charleston econometric model (CEM) (Fishkind et al. 1978; Ellson et al. 1984);
3. Impact Analysis for Planning (IMPLAN) (Charney 1997; Palmer et al. 1985; Rickman and Schwer 1993, 1995; English 2000; MIG 1999);
4. Massachusetts Economic Policy Analysis model (MEPA) (Treyz et al. 1980a,b);
5. Regional Economic Models, Inc. (REMI) (Treyz et al. 1992; Rickman and Schwer 1993, 1995);
6. Regional Input-Output Modeling System II (RIMS II) (Cartwright et al. 1981; U.S. Department of Commerce 1997);
7. Regional Science Research Institute model (RSRI) (Stevens et al. 1983; Regional Science Research Institute 1996);
8. Southern California Planning Model II (SCPM2) (Richardson et al. 1993; Gordon et al. 1998, 2001; Cho et al. 2000, 2001);
9. South Carolina Quarterly Model (SCQM) (Guimaraes et al. 1993);
10. Washington Projection and Simulation Model III (WPSM III) (Bourque et al. 1977; Bourque 1990; Conway 1990);
11. Brocker (1998);
12. California Computable General Equilibrium (CGE) Model (CAGCE) (Hoffmann et al. 1996);
13. Liew and Liew (1984, 1991);
14. Park and Schwann (1999);
15. Rose et al. (1997);
16. West and Lenze (1993, 1994);
17. California Urban Futures 2 (CUF-2) (Landis 1994a, 1994b; Landis and Zhang 1998);
18. Disaggregated Residential Allocation Model/Employment Allocation model (DRAM/EMPAL) (Southworth 1995; National Risk Management Research Laboratory 2000); and

We have tried to make a comprehensive selection, and have likely erred on the side of inclusion in this respect. At least three of the 19 models are land use-transportation models that are not normally classified as REIMs, but which produce outputs of similar general utility. However, there are uncontroverted other models that we have overlooked. We believe that our approach to the evaluation and comparison of REIMs is clear enough that it can easily be applied to any models not included in this note. The full score-card for this effort is shown in Table 1. The first 14 criteria are scored as either "0," the model does not satisfy the criterion, "1," the model somewhat satisfies the criterion; or "2," the model substantially satisfies the criterion. Ideally, these scores would be binary, but the models' agreement with our criteria is in some cases a matter of degree, which makes it necessary to afford an intermediate score. These scores are approximately interval. The 11th criterion is whether or not the model has been applied to the evaluation of earthquakes or other natural hazards for damage or policy assessment. The scoring on this last, nominal criterion is "A," has been applied to earthquakes; "B," has been applied to other natural hazards; or "C," has been applied to neither. See Gordon et al. (2002) for the details of this scoring procedure.

**Summary and Conclusions**

**Meeting Key Criteria**

What do these 11 criteria tell us about the state of art of regional economic impact models? Can these models be meaningfully compared and evaluated? Summing scores is not useful, because not all of the criteria are equally important with respect to PBEE. Which of these modeling dimensions are most important? Our approach is to make use of the information in Table 1 by identifying the most important criteria, and then successively applying these criteria as screens to eliminate models.

These key filter criteria are "spatial disaggregation" and "model integration." Although other attributes are also desirable, these two criteria are absolutely necessary for effective PBEE. Earthquakes have differential consequences at the micro-spatial level, and only very gross impacts can be measured at the county level.

The capacity for a regional economic impact model to be integrated with other earthquake engineering, transportation, network, social assessment models, and other models is vital if structural damage is to be linked to economic performance. We require models that pay serious attention to the complex interactions of economic and engineering systems and variables. In total, only four of the 19 models successfully passed through these two filters. These are SCPM2, Rose et al., DRAM/EMPAL, and UrbSim. We examine these in closer detail, along with one model that did not pass our initial screen, HAZUS. The HAZUS is perhaps the best known and most frequently applied regional economic impact model in this context, and it is intended specifically to translate the impacts of natural disasters into societal impacts.

The DRAM-EMPAL model and UrbSim are urban transportation-land use models. Despite their various merits, they are less than ideal for earthquake impact analysis. First, they take aggregate regional growth forecasts as exogenous, and then allocate these over geographical space. In contrast, the first three models measure the impact of an earthquake as a deviation from a regional baseline forecast. And second, while the latter two models are integrative in the sense that they are combined with other economic and planning models, they have not been integrated with engineering models. This leads to a third hurdle. To our knowledge, DRAM-EMPAL, and UrbSim have never been applied to the analysis of earthquakes or other natural hazards. While it may be possible to apply these models to hazard scenarios, the path to implementation is not obvious and could be very difficult to complete.

The HAZUS, SCPM2, and Rose et al. models also include important limitations. The HAZUS model has minimal endogene-
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**Table 1. Evaluation Score Summary by Model**

**Model structure/functionality**

| Policy relevant     | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Spatial dimension   | 2 | 2 | 2 | 0 | 2 | 1 | 1 | 2 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 2 | 2 | 2 | 2 |
| Interindustry       | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Integrative         | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 1 | 1 | 0 | 1 | 2 | 1 | 1 | 2 |
| Dynamic analysis    | 2 | 1 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 2 |
| Degree of endogeneity | Price adjustments      | 1 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Technology change   | 0 | 0 | 0 | 2 | 2 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| Travel behavior     | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 2 | 2 | 2 |

**Model operationality**

| Transferable        | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Empirical viability | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Accessible          | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 0 | 1 |
| Updatable           | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |

**Application**

| A | B | B | B | C | C | A | A | B | C | C | C | A | A | B | C | C | C | C |

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*Evaluation criteria and subcriteria scale: 0=no, the model does not meet the criterion; 2=yes, does meet the criterion. 1=model somewhat meets the criterion.*

*Especially with respect to infrastructure.*

*A=model has been applied to earthquake analysis; B=model has been applied to other natural hazard analyses; C=model has been applied in neither context.*
ity, and is not open code. The SCPM2 is not dynamic in the true sense, and its endogeneity is limited to travel behavior. However, current extensions incorporate endogenous price (ripple) effects to accommodate the cost increases associated with a large and rapid bridge reconstruction program. The Rose et al. model is not dynamic either. It has been applied at the county level and standard electricity service areas, many of which are too large to use for identifying differential local earthquake impacts. It lacks the transportation network, because this was not related to primary research goal, for which the model was formulated. This is a serious constraint, because an explicit representation of the transportation network is critical to analyzing the disruptions to the transportation system that will likely result from a large earthquake.

In summary, none of the 19 models investigated here fully satisfy the criteria we set forth, but the Rose et al. model and SCPM2 satisfy the largest number. An accessible version of HAZUS might do better than either, but it is obviously more difficult to evaluate a model that is not open code. At a minimum, further improvements in the Rose et al. model and SCPM2 suggest an efficient research strategy that involves building on substantial modeling achievements.

Model Validation

The most promising models reviewed here are data-intensive, large-scale, computationally demanding representations of complex systems. By their nature, they are difficult to validate. This presents a serious research challenge. Empirical opportunities are limited because earthquakes in major metropolitan areas are infrequent, and postevent data collection is expensive. However, most of the models reviewed here are certainly subject to sensitivity analysis, permitting competing earthquake scenarios may be compared. This makes it possible to compare changes in model outputs with expectations based on knowledge of the affected economies and the models’ respective formulations. Equilibrium seeking models that are based on economic principles also permit standard comparative statics analysis.

Elevating Role of Regional Economic Impact Models in Performance-Based Earthquake Engineering

Linking engineering design decisions and policymaking requires numerous simplifying assumptions. Input-output analysis, for example, has no capacity to model the input substitutions in production that may be prompted by various shortages. It is unknown how many such substitutions can reasonably be expected in the short run. Transportation network models predict steady state flows that are unlikely to be achieved if travelers and shippers lack information about the costs of alternative routes. Further, the inputs from engineering models are themselves realizations of a series of embedded distributions. There is uncertainty in earthquake hazards, soil responses to known events, and structural responses to peak ground accelerations.

Regional economic modeling makes use of the PBEE outputs characterized by Cornell and Krawinkler. Extending the PBEE framework to take advantage of regional economic impact models requires that Cornell and Krawinkler’s damage measures, perhaps measured as replacement costs; be translated into losses of building function; which most, in turn, be converted into an estimate of regional economic loss. Our review highlights the regional economic impact models that estimate regional losses. These losses are logically conditioned on losses of building function. However, there is considerable uncertainty with respect to how losses of building function are conditioned on damage measures, and considerable work to be done in this dimension.

Taken literally, Cornell and Krawinkler’s approach requires integration of parameterized, closed form cumulative probability functions. In contrast, REIMs are deterministic. However, in most cases, Cornell and Krawinkler’s approach cannot be operationalized with closed form mathematics. It is apparent to us that modeling to support performance based earthquake engineering objectives will ultimately consist of combining Monte Carlo simulations with parameterized functions. Some REIMs fit into this framework nicely. Deterministic REIMs can certainly be applied to Monte Carlo realizations drawn from parameterized or other distributions associated with research on replacement cost estimation, structural analysis, and hazard analysis.

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