

Consequence-Based Engineering Approaches for Reducing Loss in Mid-America

by

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1. Introduction

The Mid-America Earthquake Center has been recommended for a five-year renewal based on a newly directed research plan that shall ultimately reduce earthquake losses and thus risk. Intrinsic to the new plan is development of a new engineering approach to loss reduction, termed “Consequence-Based Engineering,” which is a systems-based methodology for minimizing seismic risk through selective intervention to critical components of a respective system. A brief description of the new CBE approach is given, followed by an identification of barriers that must be overcome for its development and subsequent implementation. These barriers help define the essential ingredients of a core research program directed at development of the new paradigm. A summary of this new research program is given to demonstrate how a program of coordinated, systems-driven research can be applied towards development of a new engineering concept, and to help identify possible areas of mutual future collaboration with potential stakeholders, practitioners and other researchers.

2. Description of Consequence-Based Engineering

Consequence-Based Engineering is a new paradigm for seismic risk reduction across regions or systems, which quantifies the risk to societal systems and subsystems by working with policy-makers, decision-makers and stakeholders to ultimately develop risk reduction strategies and implement mitigation actions. With a coordinated approach to engineering on the basis of anticipated consequences across systems rather than individual structures, a user of CBE can assess probable seismic hazards, synthesize damage likely across regions of specific stakeholder interests and minimize consequences of such an event through selected interventions. Because social-economic impact is considered across a population of construction, the benefits of seismic risk-reduction measures can be better assessed through this new systems approach.

The new paradigm is intended for use by practicing engineers responding to needs of their clients who have a significant vested interest in mitigating seismic risk and are thus termed “stakeholders.” Stakeholders are groups or individuals making decisions to invest in a particular intervention to mitigate possible earthquake losses. Examples of stakeholders relying on the results of a CBE analysis include insurance executives, city managers, state highway officials, and owners of large building stocks. Using new technologies that support CBE, practitioners will be able to demonstrate to their stakeholder clients via high-end data-mining and visualization tools, what types of consequences are likely for their respective systems, and

how various intervention measures, such as retrofit or relocation of structures, can reduce such consequences.

Consequence-Based Engineering is a sequence of processes and decisions that identify what consequences are possible from a probable hazard, and the impact of specific mitigation interactions on reducing these consequences across a system of interest. The steps of a CBE analysis are given in the flowchart of Figure 1 which is taken from Reference 1. Initially, a rapid assessment is done to define the relevant system, approximate the probable hazard, project what consequences are likely and delineate what types of consequences might be acceptable. Then, a four-step decision tree is used to determine if: (a) estimated consequences are acceptable, (b) if acceptable consequences should be redefined, (c) if modeling parameters should be refined and (d) if further system interventions should be considered. If anticipated consequences exceed tolerable ones, and no further redefinition of acceptability is feasible, then parameters defining the hazard and built environment can be refined to reduce anticipated losses (assuming that the preliminary analysis were conservative), and/or system interventions can be prescribed to minimize anticipated losses. An interactive damage synthesis module developed with advanced data mining and visualization tools is used to determine and view consequences for various problem definitions and mitigation scenarios. Using this module iteratively, consequences can be estimated for a number of different system intervention strategies with various input parameters describing the hazard or the built environment.

CBE technologies provide an engineer with the tools and approach needed to communicate possible consequences, and how they vary with different system alterations, in such a manner that the benefits of mitigation actions can be clearly envisioned. The CBE paradigm is new to engineering practice in that mitigation action plans are prescribed in an optimal way that minimizes risk across an entire system of interest rather than present practices of specifying unrelated risk-reduction measures for individual structures. The paradigm is expressed generally to apply to various systems ranging from the built environment across a small community to an entire national transportation or utility network.

An engineer can adopt the CBE approach today using existing tools for estimating hazards, vulnerability and loss. However, the method will become much stronger and effective as research is done using advanced technologies to develop state-of-the-art tools for risk assessment and its visualization, in addition to more accurate information on the nature of earthquakes and the response of the built environment to them.

The primary tool necessary for the full implementation of Consequence-Based Engineering is a visualization module that will synthesize response and damage across a specific region, estimate resulting economic and human losses and postulate likely consequences of the event. The speed and capacity of this new computational tool will permit fast execution and visualization of large data sets and thus enable the module to be used in an interactive mode by a practitioner working closely with a client stakeholder to evaluate the effectiveness of various mitigation action plans. Current and future developments in information technology will be exploited to develop the capability to synthesize large amounts of information describing the seismic hazard, inventories of essential features of a system including depictions of the built environment and the socio-economic system, and their resulting vulnerabilities. Virtual reality visualization of anticipated consequences across a particular region of interest will be possible with these new damage synthesis modules.

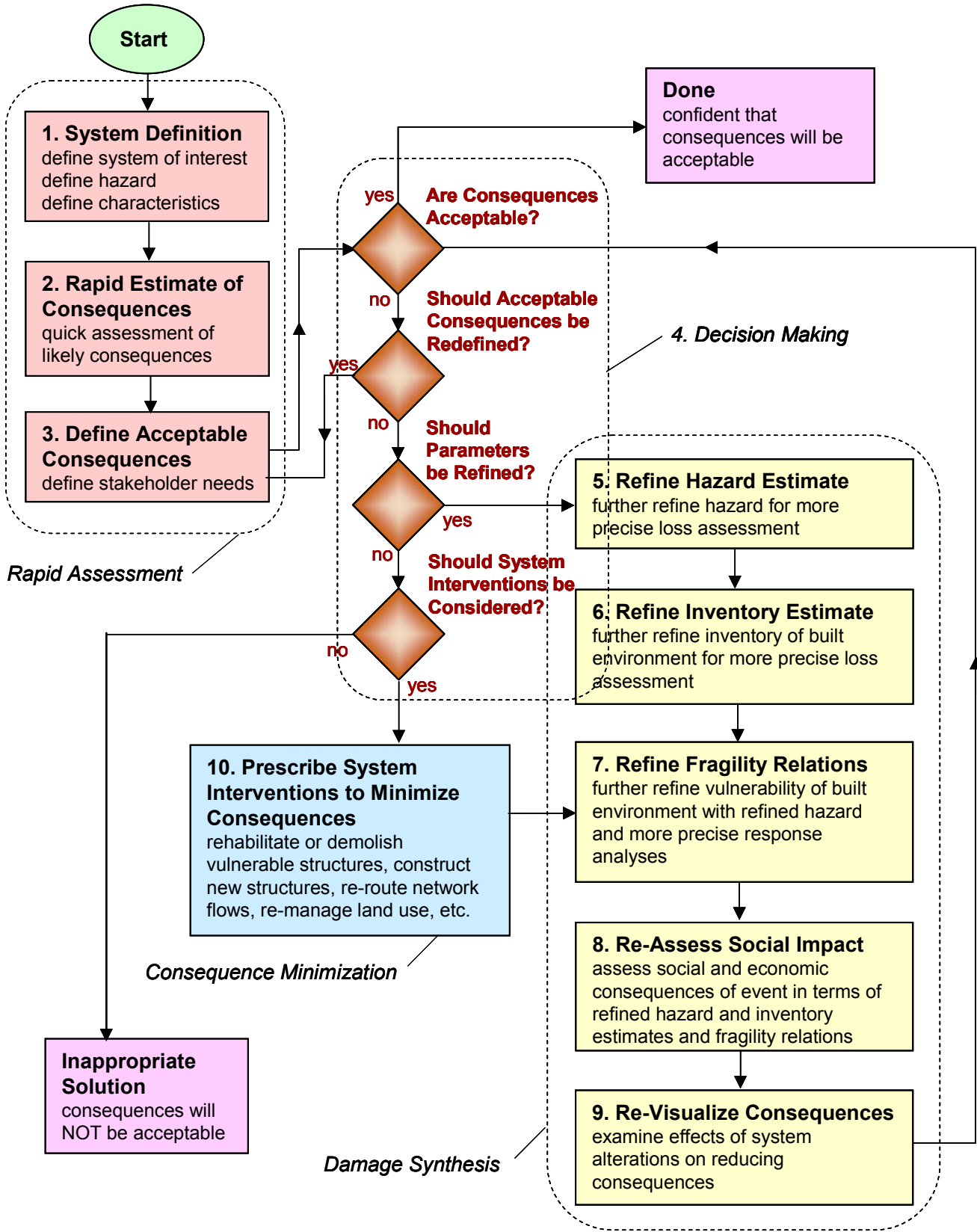


Figure 1: Flow Chart for Consequence-Based Engineering

Using the damage synthesis module, the effects of various system intervention strategies can be explored in an overall effort to select the most cost-effective solution for minimizing consequences to acceptable levels. Such intervention strategies do not necessarily entail new technologies nor require new research for their development. In some cases, consequences can be minimized by demolishing vulnerable critical components of a system and replacing with newly constructed facilities. Research may be needed to develop more effective means for demolition of existing structures or construction of new ones, but is not needed within the context of developing the CBE paradigm. Correspondingly, consequences related to component damage of network systems may be ameliorated through the re-routing of network flows. Whereas research is needed to develop methods for establishing priority routes in case of an emergency, the physical action of rerouting obviously needs no research.

In contrast, new research needs for structural intervention may be identified using the CBE paradigm. Critical components of a system may be found to be vulnerable and in need of selective rehabilitation. For example, piers supporting a critical approach to a major river crossing could be found to lack the strength or deformation capacity needed to support the approach during an earthquake, and thus limit functionality of not only the approach, but also the bridge and the surrounding transportation network. In such case, research on rehabilitation techniques for this particular type of pier would be cost effective because consequences could be significantly minimized. Similar examples can be given for the importance of rehabilitation for structural components of other stakeholder systems.

3. Barriers to Development of CBE

The CBE paradigm can be used with current technologies for defining the seismic hazard, collecting inventory information, estimating vulnerability functions and assessing losses. However, the worth of the new engineering approach will not be fully appreciated until the following barriers are overcome through future research.

1. Standard procedures need to be developed for rapid estimates of consequences from approximate definitions of systems.
2. A standard approach needs to be developed for identifying what consequences are acceptable for various stakeholders. A study of acceptable consequences for a number of different stakeholder systems and scenarios is needed to gain perspective on how practitioners should resolve with their stakeholder clients what their acceptable consequence levels may be, and how much redefinition of these levels may be possible.
3. Basic studies of decision making need to be done to identify: (a) how various stakeholder groups react to anticipated consequences, (b) to what extent a stakeholder will be willing to invest in parameter refinement and/or system intervention to reduce consequences, and (c) what types of system intervention are attractive to stakeholders for reducing consequences of earthquake and other hazards.
4. Tools need to be improved for estimating seismic hazards in regions where earthquake records are sparse. Hazard maps and synthetic ground motions are needed to refine seismic hazard estimates from current information. Basic knowledge of source, path and site effects for infrequent, high consequence earthquakes needs to be improved for development of ground-motion simulations. Better information is also needed for improvement of ground-failure modeling in such regions.
5. The most relevant parameters of regional inventory information, essential to precise loss assessments, need to be identified. New survey techniques based on advanced technologies need to be developed so that inventory data can be collected quickly and inexpensively, and yet be the bases for precise consequence estimates.

6. New structural analysis tools need to be developed for estimating seismic response of a wide variety of existing and rehabilitated construction systems. Simple, yet accurate response estimates are needed to generate fragility or vulnerability functions for categories of construction types.
7. Approximate vulnerability functions representing categories of typical construction types need to be developed for quick estimates of losses across stakeholder regions.
8. Social impact assessments need to be studied for various stakeholder regions to understand how to quantify an incorporate within computational models.
9. A highly capable, consequence visualization module needs to be developed exploiting recent advancements in information technology to synthesize information and data on the seismic hazard, regional inventory, seismic response and vulnerability and socio-economic impact. This module is the central engine of the CBE paradigm, and is essential for running a number of quick, but precise, iterations depicting consequences across a region.
10. Interventions to minimize consequences across specific stakeholder regions need to be developed. Such measures may include new technologies for rehabilitation of vulnerable construction types identified as critical to system performance, re-routing of network systems or re-management of land use across particular stakeholder regions.

4. MAE Center Core Research Program

Interdisciplinary expertise of MAE Center researchers in earthquake risk mitigation is coordinated within a new research plan to develop appropriate and novel technologies needed for implementation of the CBE paradigm. As well, new research talents outside of the Center are sought as needed to fulfill research objectives. This restructuring of the research program addresses three vital requirements, namely: (a) a systems-driven research program that seeks new technologies and fundamental knowledge as needed for development and use of the paradigm, (b) interdisciplinary teaming of researchers at the project level, and (c) involvement of industry partners in development of core research to ensure its implementation potential and application to stakeholder needs.

Several new projects are formulated to meet requirements of a fully CBE-driven program within the systems approach adopted by the Center during the strategic planning phase. The three core thrust areas noted in Figure 2 are defined to provide technologies and necessary knowledge to support general development of the CBE paradigm. Each core research thrust area is designed based on a potential for extrapolation to stakeholder needs through external industry funding.

Each of the three core areas do not stand alone in achieving Center goals, but combine with one another and with future stakeholder thrusts to develop the CBE framework. The nucleus of the three core areas is a series of three overarching projects comprising the **CBE Framework Development (FD)** that synergizes core research by providing the philosophical, theoretical and operational backbone to the whole Center research program. A highly interdisciplinary thrust named **Damage Synthesis (DS)** is aimed at providing advanced and reliable tools for estimating

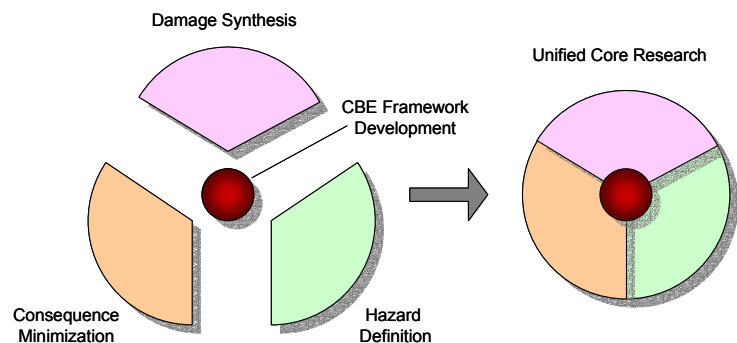


Figure 2: Core Research Thrust Areas

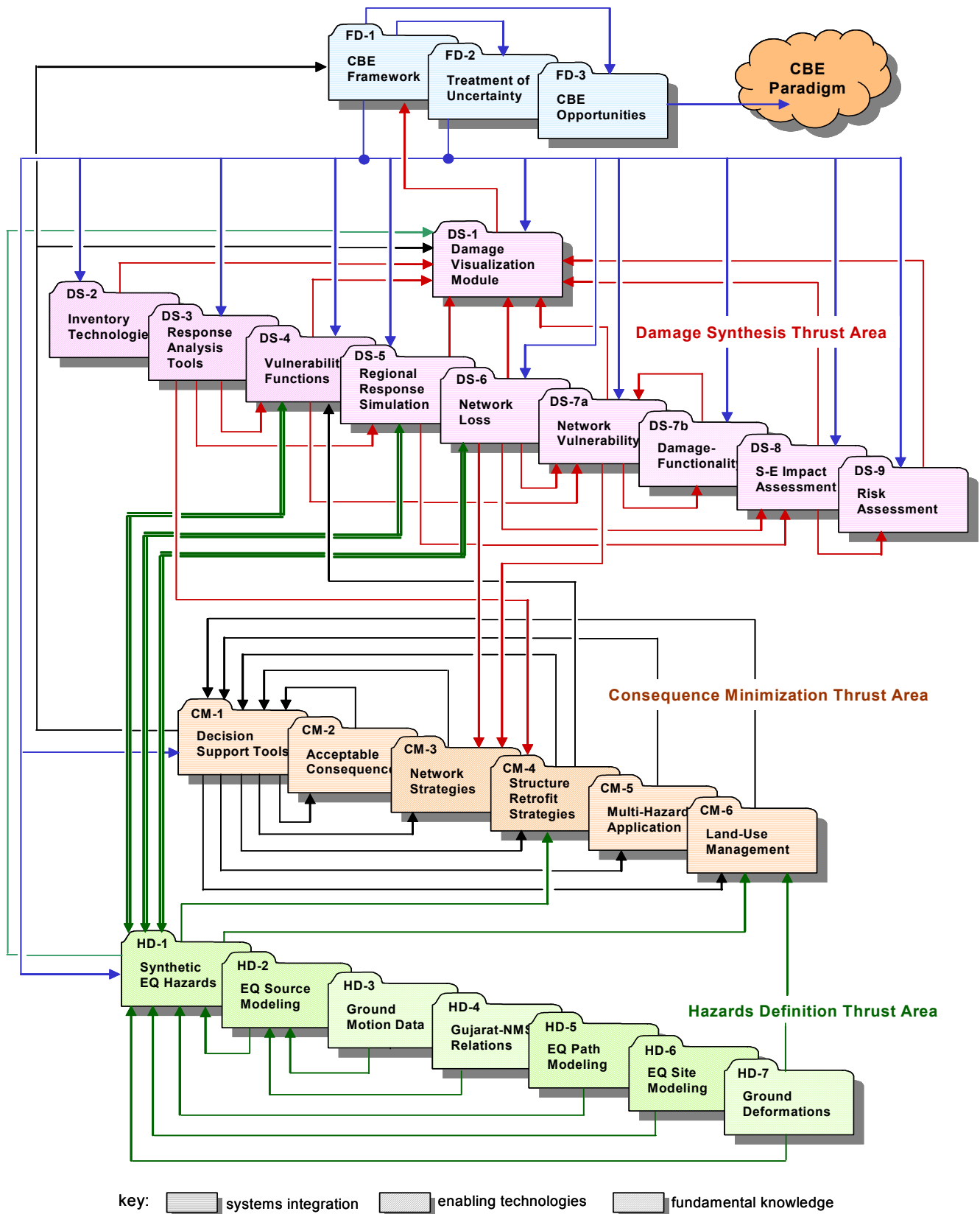


Figure 3: Outputs and Inputs from and to Core Research Projects

consequences of earthquakes across vulnerable regions, including all aspects affecting intricate societal systems common to communities and national networks. A second core thrust area entitled **Consequence Minimization (CM)** focuses on the use of the damage synthesis module through research developing decision support tools, improved understanding of acceptable consequences, and enhanced intervention strategies for optimizing reductions in anticipated consequences. In service to both of these thrust areas, a third thrust area on **Hazard Definition (HD)** provides updated and reliable hazard indicators both in a generic manner and specific to the primary geological test-bed region of Mid-America.

Viewing the Consequence-Based Engineering framework development as a driving force and ultimate objective for the three core research thrust areas focuses attention within the Center, and externally, to its role in developing the new paradigm that will be extendible to seismic regions beyond Mid-America, as well as to systems worldwide subject to hazards other than earthquakes. As noted in the preceding sections describing Consequence-Based Engineering, steps of the engineering process are categorized with respect to rapid assessment, decision-making, damage synthesis and consequence minimization. The process flowchart for CBE, as described in detail in Figure 1, is itemized in terms of a series of ten steps. Because research needs are not uniformly necessary across each task of the CBE framework, a one-to-one mapping of research projects and paradigm steps is neither appropriate nor intended. However, objectives of the new Center core research thrust areas, as described below, clearly reflect research needs for development of the paradigm.

Inter-relationships among individual projects are manifested in the form of a flow chart (Figure 3), where inputs into and outputs from all projects are shown, towards the development and articulation of the CBE paradigm. Considerable attention is given to the inter-dependencies of each research project relative to each other and each research thrust area. Detailed project summaries can be found on the MAE Center website (<http://mae.ce.uiuc.edu>) that describe the co-dependencies noted in the flowchart. As noted in Figure 3, one project of each thrust area is primary for assimilating results from other research projects. The damage visualization module (project DS-1) is central to the Damage Synthesis thrust area because it integrates tool development for collection of inventory data, for estimating seismic response and resulting vulnerability, for estimating social and economic impact, and for modeling risk. Correspondingly, a project on probabilistic support tools (CM-1) is pivotal to the Consequence Minimization thrust area since it dictates the need for, and collects the results from, projects on defining acceptable consequences, and developing intervention strategies. Lastly, a project on synthesizing seismic hazards (HD-1) serves as a primary conduit for research results from projects focusing on source, path and site effects as well as ground deformations. Overarching projects on development of the CBE framework (FD-1), modeling of uncertainty (FD-2) and CBE opportunities and challenges (FD-3) help to direct all projects of the program towards practical implementation of the new paradigm.

5. Balancing the Core Research Program

Strategic planning evolved based on the premise that research should be system driven according to the needs for development of the CBE paradigm. The three-plane chart shown in Figure 4, was used to establish the context of each research project with respect to its relevance for integrating regional system aspects, for contributing to new technologies needed to enable use of the CBE approach, or for supplying basic knowledge as needed to support applied research. Research project themes, noted to the right in the figure, are separated as to their relevance to each plane. Each research theme is represented in the research plan with one or more projects devoted to it. Deliverables and milestones are identified for each project in the following plan that fall within the categories shown as needs and outputs between each plane.

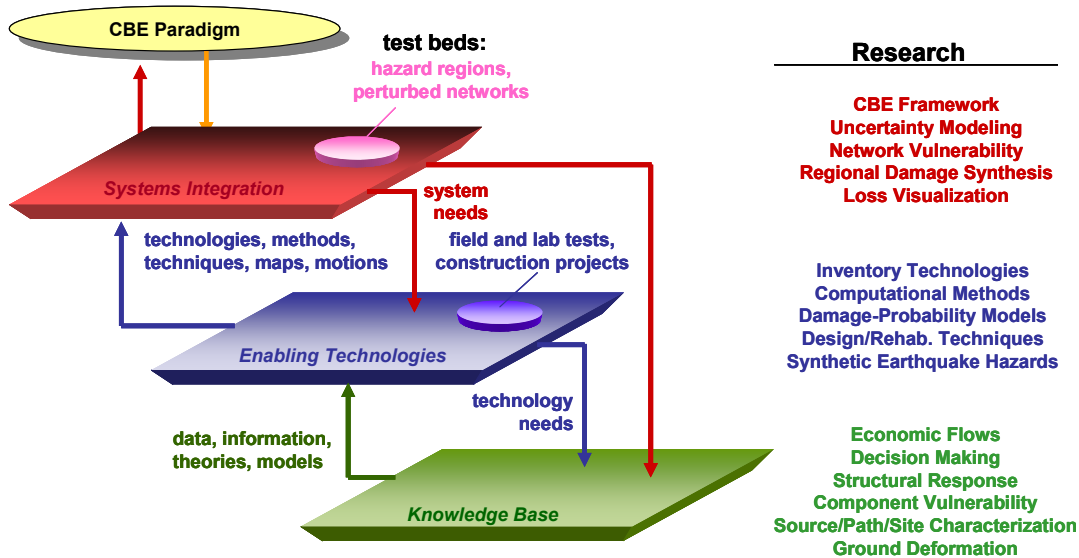


Figure 4: Balance of Research between Systems Integration, Enabling Technologies and Knowledge Base

Test-bed applications are also delineated in the plan that confirm and calibrate tools and models developed with projects associated with the upper two planes of the diagram.

Systems integration research shown on the top plane includes the project (FD-1) on development of a CBE framework that is the central driver linking research needs of the paradigm development to research of the core and stakeholder thrust areas. Closely associated with this framework project is the project on uncertainty modeling (FD-2) that provides an ability to reflect key problem uncertainties in future selection and funding of projects. Other systems integration activities include the overall thrust efforts on synthesizing damage across regions and modeling vulnerability of networks, as well as the capstone project that uses advanced information technologies for visualization of synthesized damage and loss across regional systems.

Research on the enabling technology plane includes advanced technologies for more rapid and accurate inventories of the built environment across regions or networks, new computational methods for estimating seismic response of the built environment (for purposes of regional damage synthesis, or engineering of individual structures), new modeling approaches to assess vulnerability of systems and components, new engineering techniques to improve seismic safety and performance of new and existing construction, and updated hazard descriptions. Needs for fundamental knowledge are driven by both system-level research as well as enabling technology research and includes basic social science studies of organizational decision making, dynamic response of structural systems and behavior of components and materials, and the basic nature of ground motions and ground failures including liquefaction.

6. Stakeholder and Practitioner Participation in Center Research

The structure of the Center's research program is based on the marriage of three core research thrust areas with four stakeholder research thrust areas representing insurers, owners of large building stocks, construction associations and transportation officials. To maximize leveraging potential, core thrust area research, supported with NSF and institutional matching funds, is implicitly intended to serve research interests of not one, but multiple, stakeholder groups as

denoted graphically in Figure 5. In turn, research of individual stakeholder groups extends core research towards applications pertinent to their respective goals. Thus, neither core or stakeholder research thrusts, by themselves, can provide the appropriate balance between systems, enabling technologies and basic knowledge. However, combinations of carefully configured core research with individual stakeholder research will result in balanced research agendas having the most impact on earthquake risk reduction.

Though perspectives on CBE utilization may vary with each stakeholder group, common interests exist on its further development, and thus, each stakeholder group has an interest on how core research is done to advance the new paradigm both within and external to the core research. The strategy for stakeholder participation is critical for communicating to partners on how the new paradigm can reduce seismic risk for their industries, facilitating their input for planning of future directions for research and education programs of the Center, and attracting external research funding from them supporting both the core and stakeholder programs.

Apart from stakeholders, a second group with an interest in Center research is engineering practitioners who will be early adopters of the CBE paradigm. Whereas consulting firms do not generally fund research, advice of practitioners with respect to the practicality of implementing a new engineering approach is essential for its ultimate success. Consultants with experience in providing seismic risk assessments for stakeholder clients will be selected to advise the Center on its CBE-directed research program.

The organization of the Center's research into core thrust areas and stakeholder thrust areas is key to its strategy for attracting strong in-kind and direct support from industry and government partners. Each of the four stakeholder groups has been selected because of their diverse perspectives regarding seismic risk reduction. The group of insurers is primarily interested in quantifying risk across a region to set fair premium and deductible rates to cover anticipated insured losses. Construction associations are interested in respective market shares for their particular construction types, and thus the most economical solutions for seismic safety in regions of variable earthquake intensity. Owners of large building stocks are primarily interested in probable damage to their property as it relates to the safety of inhabitants and continued building operation. State transportation officials are interested in assessing and minimizing consequences (perturbations to economic flows, emergency response, health care, business loss, etc.) associated with a loss of function across their networks. Yet each stakeholder group has something in common – that is to be able to synthesize damage for their particular systems across specific regions of interest, and thus visualize consequences of a future hazard in such a way as to influence decision makers. Thus, each stakeholder group has an interest in supporting core research.

Whereas stakeholders have interests according to their specific perspectives, they also have motivations for adopting and developing the general CBE paradigm. Such motivations are summarized in Table 1 along with listings of refinements to CBE that each stakeholder group would be interested in developing. These listings are suggestive in nature to help illustrate why stakeholders are willing to support core research towards the CBE paradigm, and how stakeholder research thrust areas can extend results of core research to particular applications. Future meetings of each stakeholder group will be held to further articulate these motivations and refinements, and to prioritize research needs for both core and stakeholder research thrust areas.

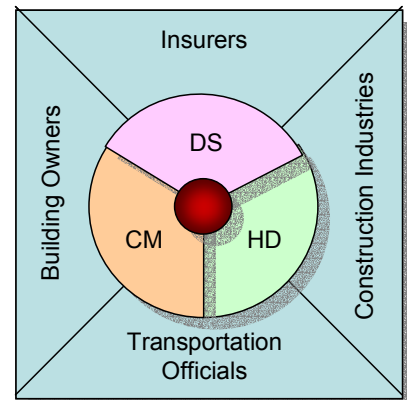


Figure 5: Stakeholder Thrust Areas

Table 1: Stakeholder Motivations for Adopting CBE and Pertinent Refinements

Stakeholder Group	Motivations for Adopting General CBE Paradigm	Stakeholder-Specific CBE Refinements
<p>Transportation Officials</p>	<ol style="list-style-type: none"> Better understanding of vulnerability for transportation networks. More rational network retrofit and rerouting strategies. Better tools for visualizing earthquake consequences across transportation networks. 	<ol style="list-style-type: none"> Use of advanced aerial reconnaissance techniques for inventories of transportation networks and loss assessments. Response and vulnerability estimates for bridges and other transportation structures. Improved rehabilitation methods for bridges and other transportation structures. Network performance during and after earthquakes including designation of emergency escape routes.
<p>Building Owners</p>	<ol style="list-style-type: none"> Better understanding of property losses and seismic risk. More economical ways to reduce risk through mitigation. 	<ol style="list-style-type: none"> Inventories of specific building stocks. Damage synthesis for specific groups of buildings. Definition of acceptable consequences for specific building types. Effect of intervention technique on losses for populations of buildings of a particular construction type. Seismic resistance of gravity-load designed buildings. Multi-hazard resistance of seismically rehabilitated buildings. Incremental rehabilitation strategies for groups of buildings. Region-specific seismic hazard definitions.
<p>Insurers</p>	<ol style="list-style-type: none"> More precise risk assessment models. Better understanding of how mitigation can reduce seismic risk. Better tools for visualizing earthquake consequences across coverage areas. 	<ol style="list-style-type: none"> Use of advanced aerial reconnaissance techniques to assess losses. Rapid loss assessment visualization software for buildings and network systems. Damage synthesis and risk assessments for specific coverage areas. Means of gauging and influencing public perception of risk. Effects of multihazard mitigation for specific building types. Region-specific seismic hazard definitions.
<p>Construction Associations</p>	<ol style="list-style-type: none"> Impact of seismic damage on future marketability of construction type. Better understanding of anticipated damage versus construction cost. 	<ol style="list-style-type: none"> Inventories of specific construction types. Response and vulnerability estimates for specific construction types. Damage synthesis for specific construction types. Improved rehabilitation methods for specific construction types. Economic impact of new seismic code provisions.

7. Concluding Remarks

This paper has presented an overview of a new interdisciplinary research plan addressing the development of a new engineering paradigm known as Consequence-Based Engineering. Strategic planning concepts have been discussed to demonstrate how a systems-driven program of research can be targeted towards a specific goal of changing engineering practice for the better with respect to seismic risk reduction across regions of interest. Comments on the paper, the new engineering paradigm or the research program to develop it are very much appreciated, as are suggestions for collaborative opportunities.

8. Acknowledgements

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7. References

1. Abrams, D.P., A.E. Elnashai and J.E. Beavers, "A New Engineering Paradigm: Consequence-Based Engineering," paper to be submitted to *Earthquake Spectra*, Earthquake Engineering Research Institute.