COMPUTATIONAL ENVIRONMENT FOR MODELING AND ENHANCING COMMUNITY RESILIENCE: INTRODUCING THE CENTER FOR RISK-BASED COMMUNITY RESILIENCE PLANNING

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ABSTRACT

The resilience of a community is defined as its ability to prepare for, withstand, recover from and adapt to the effects of natural or human-caused disasters, and depends on the performance of the built environment and on supporting social, economic and public institutions that are essential for immediate response and long-term recovery and adaptation. The performance of the built environment generally is governed by codes, standards, and regulations, which are applicable to individual facilities and residences, are based on different performance criteria, and do not account for the interdependence of buildings, transportation, utilities and other infrastructure sectors. The National Institute of Standards and Technology recently awarded a new Center of Excellence (NIST-CoE) for Risk-Based Community Resilience Planning, which is headquartered at Colorado State University and involves nine additional universities. Research in this Center is focusing on three major research thrusts: (1) developing the NIST-Community Resilience Modeling Environment known as NIST-CORE, thereby enabling alternative strategies to enhance community resilience to be measured quantitatively; (2) developing a standardized data ontology, robust data architecture and data management tools in support of NIST-CORE; and (3) performing a comprehensive set of hindcasts on disasters to validate the data architecture and NIST-CORE.

KEYWORDS: Community resilience; hazards; investment optimization; post-disaster recovery; resilience performance metrics; risk-informed decision.

INTRODUCTION AND MOTIVATION

Disaster resilience has been defined many ways, but one major commonality exists in virtually all definitions: the ability to rebound following a shock or major disruption. Presidential Policy Directive (PPD) 8: National Preparedness (2011) defines resilience as the ability to “adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies.” This definition was expanded in Presidential Policy Directive (PPD) 21 (2013) which defines resilience as the ability to “prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.”   The ability of a community to recover from a disaster is a function of many factors including pre-event planning, preparation, mitigation, infrastructure type, complexity, condition, individual and collective experiences prior to the disaster and the ability to mobilize resources afterward. Prior to the disaster, a community may contain a heterogeneous mix of populations and institutions of varying degrees of vulnerability. Following the occurrence of an extreme event, there is a rapid drop in community functional capacity, followed by a period of response and recovery, leading to a “new normal” state for the community. For example, the most vulnerable communities may have a diminished “new normal,” in which the community functions at a level that is below where they were prior to the event because they were only able to build back based on pre-impact or diminished capabilities; an example of this is the City of New Orleans, Louisiana, USA shown flooded in Fig 1a following Hurricane Katrina in 2005, particularly in the lower 9th ward. Conversely, communities may achieve a “new normal,” in which their community functions at a higher level following the event, in what has been termed a “build back better” scenario. An example of this is Greensburg, Kansas, USA following the 2007 EF5 (> 320 kph winds) tornado, in which 95 % of the city was destroyed as shown in Fig 1b.

(a) (b)

Figure 1 (a) New Orleans, LA during flooding following hurricane Katrina in 2005 (Ed Levine, NOAA); (b) Greensburg, KS following the EF 5 tornado in 2007 which destroyed 95 % of the city (Greg Henshall, FEMA)

The performance of the built environment in the United States, which is a key factor in community resilience, is largely determined by codes and standards, which are applicable to individual facilities and residential structures, and have the primary objective of preserving life safety under severe events. Current codes do not address the period of recovery following an event. Moreover, design of interdependent transportation systems, utilities and communication systems currently is based on different performance criteria. As a consequence, there currently is no assurance that all systems required for community resilience will perform at a necessary or consistent level following an extreme event. Uncertainties in the demands placed on a community by extreme natural hazards and in the response of community infrastructure to withstand those demands are very large. Furthermore, science-based measurement tools to evaluate performance and resilience at the community scale, fully integrated supporting databases, and risk-informed decision frameworks to support optimal life-cycle technical and social policies aimed at enhancing community resilience do not exist. The NIST-CoE will focus on creating these science-based measurement tools over the next five years. These tools will allow researchers and planners to assess strategies quantitatively for optimizing resiliency subject to a community’s technical, economic and social constraints. The risk-informed decision framework and unique set of science-based measurement tools will help communities to better assess, visualize and potentially achieve resilience goals while managing life-cycle costs, thus making it possible to establish, for the first time, a business case agreed upon by a communities multiple constituencies, for achieving community resilience.

OVERVIEW OF THE CENTER FOR RISK-BASED COMMUNITY RESILIENCE PLANNING

The NIST-CoE at Colorado State University, funded by the National Institute of Standards and Technology (NIST), will develop systems-level models and databases that will provide the technology for enhancing community resilience in a research and development program. In addition to faculty at CSU, the team members include noted experts in resilience from the California Polytechnic University Pomona, Oregon State University, Rice University, Texas A&M University, Texas A&M University-Kingsville, the University of Illinois at Urbana-Champaign, the University of Oklahoma, the University of South Alabama, and the University of Washington. The Center’s research program is organized along three major thrust areas.

Thrust 1 will develop a multidisciplinary computational environment with integrated supporting databases, known as NIST-CORE (NIST-Community Resilience Modeling Environment), that will enable the factors (and their inter-relationships) that determine community resilience to be better understood. This environment is being implemented as a risk-informed decision framework that permits the effectiveness of alternative strategies for addressing resilience to be measured quantitatively. A distinctive feature of Thrust 1 is its emphasis on multiple hazards and inter-dependent physical systems, which may have significant cascading effects. This will include consistent handling of and propagation of uncertainties throughout the analysis. Furthermore, nontechnical systems that are essential for the recovery and vitality of a community – housing, businesses, healthcare, schools, and civic organizations – are being integrated into NIST-CORE, creating a nexus between social and technological infrastructure networks intended to narrow the gap between engineering and social science aspects of resilience planning and to facilitate risk communication among stakeholders. Finally, optimization strategies for enhancing community resilience involving advanced intelligent decision algorithms are being integrated, and are based on performance metrics such as time to recovery, number of mortalities, number of morbidities, and other metrics to be identified.

Thrust 2 will produce a CoE standardized data ontology, a robust data architecture, and effective data management. This includes tools to support the computational environment developed in Thrust 1 and to permit databases from stakeholders representing multiple domains of engineering and social sciences to be integrated to the decision process. The data architecture and data management tools in NIST-CORE will be customized to help users incorporate, manage, query, visualize and share data.

Finally, Thrust 3 will validate the resilience data architecture through a series of testbeds that stress the process of data collection, its integration into the computational modeling environment, and decision algorithms. The NIST-CoE research thrusts seek to align with those of NIST, with synergies and opportunities for collaborative research, staff exchanges, development of partnerships with the private sector, and for participating in collaborative field studies that can be used to validate and improve the computational environment and its supporting databases.

THRUST 1 - COMPUTATIONAL MODELING ENVIRONMENT FOR COMMUNITY RESILIENCE: DEVELOPMENT OF NIST-CORE

The NIST-CORE architecture is depicted in Fig 2. When fully developed, NIST-CORE will have the capability of computing proposed resiliency assessment measures at the user-specified community level (described to the right in Fig 2) and utilizing the data architecture (summarized at the bottom of Fig 2), thereby producing performance metrics, performance requirements, and risk-informed decision tools for community resilience. This section addresses some of the immediate challenges that Center investigators are addressing.

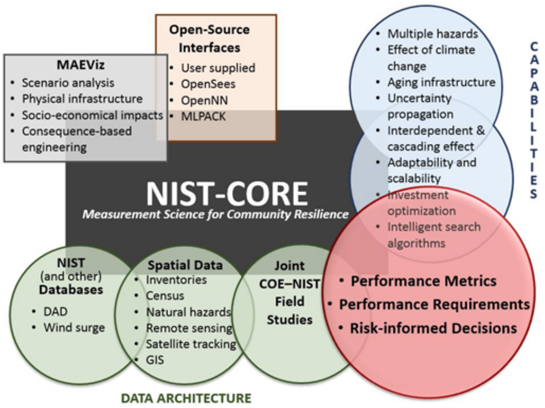

Figure 2 The architecture of the NIST Community Resilience (NIST-CORE) Modelling Environment

Hazards and Climate Change

The treatment of hazards, including earthquake, earthquake aftershock, coastal and riverine flooding, tornado including wind and debris, hurricane wind and debris, hurricane surge and wave, wildfires and their interface with urban areas, tsunami, and landslide, is a major part of the NIST-COE. The risk formulation for some individual hazards is reasonably mature; for other hazards, there is a need for improved characterization of intensity and damage potential for the computational resilience modeling environment. For example, wind speeds resulting from tornadoes are not well developed but have been recently updated by, for example, Standohar-Alfano and van de Lindt (2014) by combining earlier methodologies. Relative to seismic and wind hazards, the hazards due to surge, waves, and water-borne debris for hurricanes and severe coastal storms have been identified as a critical research gap (NIST 2014), not only for characterizing the probable inundation levels and wave conditions but also for identifying the joint distributions of wind and wave effects for multi-hazards scenarios. Moreover, recent research (Tamiczek et al 2014) following Hurricane Ike has shown that water depth alone is often a poor predictor of damage to structures. Each of these cases requires special consideration with regard to the specific multi-hazard models for: a) multi-hazard characterization, b) modeling infrastructure fragilities when subjected to concurrent or time lag events; and c) restoration modeling.

In addition to consideration of hazards, the NIST-CoE will include methods to estimate the effect of climate change on hazards when applying them within NIST-CORE. During the past three decades, evidence has grown that global climate change may affect both the frequency and severity of extreme events resulting from natural hazards (e.g., IPCC 2013). The severity of extreme climatic events is characterized by changes in the climate variables such as wind speed, precipitation, temperature or flooding. However, practically all risk assessments for civil infrastructure to date have been based on the assumption that the hazard-imposed demands on the system can be modeled as stationary random processes. This assumption becomes untenable when the effects of global climate change are considered (Lee and Ellingwood 2013). Stochastic models of natural hazard demands from hurricanes, surge and coastal flooding that incorporate nonstationarity due to changes in sea surface temperatures and other manifestations of climate change are also being developed.

Modelling the Built Environment

Five key components of the built environment are being modeled, including buildings, transportation infrastructure, water and wastewater networks, energy systems, and telecommunication networks. Performance objectives for individual buildings are required to enable a building inventory to support community resilience goals (McAllister 2013). For example, the SPUR Program in San Francisco (Poland 2011) established a set of performance objectives for buildings (e.g., hospitals, school, emergency operation centers, residences, businesses) in different performance categories exposed to different earthquake intensities (i.e. routine, expected, and extreme) and with different functionality needs (i.e., immediate recovery within 72 hrs., short-term recovery within 60 days, and long-term reconstruction).

While the SPUR Program provides an example of building performance criteria linked to community resilience planning for one hazard (earthquake), more general metrics, criteria and guidelines for building performance that are based on measurement science are required for disaster planning for communities with different hazard exposures, social needs and resources. Resilience assessment of buildings, as implemented by structural engineers for extreme events, has focused on minimizing direct and indirect losses through enhanced system robustness as well as more effective recovery strategies (e.g., Bruneau, et al. 2003).

Transportation infrastructure is comprised of a number of multi-modal systems, such as bridge and roadway networks, heavy and light rail, airports and port and maritime systems. Common themes for characterizing transportation system resilience include the need to assess component reliability under multiple hazards, model connectivity within the network, evaluate the recovery trajectory and quantify the associated impacts on community functions. A significant body of work exists on modeling the fragility of transportation infrastructure to aging, with emphasis placed on resilience assessment of bridge networks (e.g., Bocchini & Frangopol 2013), but with only limited work on other modes of transportation. In the transportation network developed within the NIST-CoE, temporal effects (e.g., aging, time lag in multiple events, sequence of restoration) will be captured along with spatial considerations across a regionally distributed network (e.g., damage correlations).

Water systems are regarded as a “lifeline” infrastructure crucial for minimizing the societal impact of extreme events. These networks are large, distributed interdependent systems and their failure can be significant, since residential, commercial, industrial, and other users depend on the network: supply (ground and surface), transmission, treatment, pumping, and storage.

Electric power delivery systems are comprised of generation, transmission and distribution subsystems and are central to the proper functioning and operation of most other infrastructure and again critical for social systems in general and business survival in particular. Thus, they have been examined in greater detail than have natural gas, liquid fuel, or geothermal systems, and models of resilience for electric power delivery networks have been developed. Most of these models focus on the resilience of the physical systems comprised of generation facilities, transmission towers, substations and transformers, poles and towers that comprise the bulk of the distribution lines.

Innovative approaches to modeling resilience and interdependency include agent-based modeling, input-output models, mathematical models and game theory. Physics-based models (as opposed to regressive models) for assessing resilience and reliability of electric power delivery include system-level fragility functions based upon multiple hazards, expanded system reliability indices as defined by IEEE 1366 (2012); post-event restoration models; functionality and inoperability models with associated metrics of "vulnerability", "rapidity" and "recovery" and mechanical analog single degree of freedom system models used to characterize the properties of the underlying system and to determine how these properties may be used minimize outage times (e.g., Reed et al. 2009).

Modelling Economic and Social Systems and Networks

Economic models can inform a portfolio of risk management investment decisions, including mitigation, warning and evacuation systems, as well as recovery and reconstruction efforts (Gilbert 2010). In short, these models can show how investing or failing to invest in resilience-enhancing interventions generate direct and cascading effects in economic systems that can alter a regional (or community) economy's long-term trajectory. Two complementary economic impact modeling approaches are being utilized within the CoE to estimate the direct and multiplier effects of assorted disaster shocks. First, *applied econometric models* examine community resilience across a variety of economic outcomes (e.g., gross regional product, government revenue, employment growth, wages, births and deaths, and migration flows) over hazard events of varying intensity (i.e., fatalities, injuries, destruction of capital stock), given varying regional attributes and levels of investment in hazard resilience. Specifically, the objective is to quantify the economic impacts of disasters in the US over the last 50 years to determine the level of resilience that has been achieved across regions. Second, *computable general equilibrium (CGE) models* capture economic dynamics during and after major shocks, analyzing how hazard losses manifest themselves in the economy of a region through industry-specific losses in capital stock, damage to critical infrastructure, and human capital stock deterioration through out-migration (Rose 2009). These models will be integrated into the intelligent decision algorithms for optimizing investments in community resilience.

The impacts of disasters on human populations (mortality, morbidity, and psychological) and social systems (disruption, displacement, failure, change), while set into motion by the particular disaster agent, are nevertheless heavily influenced by pre-existing inequalities related to physical vulnerabilities in the built and natural environment and social vulnerabilities generated within economic and social systems. Linking these physical and social vulnerabilities is key to understanding community disaster resilience. Socially vulnerable populations within communities that are residing in hazard-prone locations and vulnerable structures before a disaster often are most likely to experience disproportionate losses, higher damage rates, and housing losses (Highfield et al. 2014). Loss of housing resulting in short- and long-term displacement, jeopardizes employment, business survival, food security, educational attainment, and access to transportation and local support networks, thus placing households in even more precarious and difficult recovery trajectories (Peacock et al 2014). Variations in socio-economics results in clusters of households and businesses facing similar direct and cascading effects, leading to increased probabilities of local business disruption and subsequent failure. The ability to model cascading effects requires that these preexisting social vulnerabilities of populations and social systems characterized in terms of age, race and ethnicity, gender, income/poverty, including relative access to potentially scarce resources such as health care, food, education, employment and housing will be modeled (Van Zandt et al 2012). The way in which hazards losses manifest and cascade among these populations and social systems, such as the dependencies between housing loss, population displacement and local business and neighborhood disruption (Xiao and Van Zandt, 2013) is being modeled for synthesis into NIST-CORE.

Treatment of Interdependency, Aging Infrastructure, and Uncertainties

Community resilience is highly affected by the mutually interdependent nature of buildings, transportation, water and wastewater, power, and communications (Reed 2009). Interdependency is defined herein as "the multi or bi-directional reliance of an asset, system, network, or collection thereof, within or across sectors, on input, interaction, or other requirement from other sources in order to function properly" (CIKR 2008). Most available approaches to modeling interdependency only support a portion of the simulation (i.e., response phase, failure cascading phase, or recovery phase) involved in the resilience analysis (Ouyang 2014). Within the NIST-CoE a combination of methods to achieve a uniform interdependency modeling framework *in both time* *and geographic scale* for the overall resilience analysis in NIST-CORE will be used. Data obtained from remote sensing, satellite tracking, and geographical information systems at various scales will be integrated into NIST-CORE, which will include a combination of topological approaches, network flow models, and empirical methods. The data-rich history which currently exists (and will be continually updated and housed within NIST-CORE) in empirical methods and statistical learning will inform the topological representation and thereby improve the accuracy of the interdependencies captured by the model.

Physical infrastructure facilities may deteriorate due to exposure to extreme conditions (e.g., excessive loading or harsh environments), weathering, routine use and accidents. The past two decades have seen considerable research on time-dependent reliability of deteriorating structures (e.g., Mori and Ellingwood 1993; Frangopol, et al. 2004). To model the life-cycle of a facility, including time to failure under random occurrences of loads or number of loads until failure occurs (e.g., operational and extreme loads), stochastic models of the deterioration processes and the dependencies between these processes will be included in NIST-CORE. The models will utilize a novel framework that accounts for 1) both shocks and a gradual deterioration process; 2) the effect of deterioration on both capacity of and demand on infrastructure components; and 3) the possibility of both types of failures. The stochastic framework will be used in a novel renewal theory-based life-cycle analysis (RTLCA) model for deteriorating infrastructure components, which accounts for both functional and ultimate failures.

Significant uncertainties exist in every phase of community resilience evaluation – in the condition of the built environment prior to the occurrence of the extreme event, in the loss of functionality immediately after the event, and in the time and degree of post-disaster recovery. Essential components of uncertainty analysis include physical system-based uncertainties that mainly affect the community robustness (e.g., stemming from performance of individual facilities, building portfolios and infrastructure systems as a whole) and socioeconomic uncertainties that affect the extent of societal impact and community recovery (e.g., those associated with social, economic and political institutions within the community, human responses and available external resources.) Such socioeconomic uncertainties will be considered (Murphy et al 2011).

Resilience assessment methods developed within the last decade do not address the spatial and temporal correlations in the response of building portfolios and infrastructure systems as an integral part of the community resilience; nor do they address the uncertainties in the recovery trajectory, which depend on the residual strength of key community institutions following the disaster. NIST-CORE will incorporate simulation-based algorithms for propagating uncertainties in individual and competing natural hazards, in facility response and capacity, and in structural modeling through the risk analysis. The uncertainties in the effect of aging on capacity and demand and the effect of climate change on the intensity/frequency of natural hazards will also be addressed. Coupling and linkage of engineering and social science models of displacement and housing recovery, for example, introduce additional issues in the modeling of uncertainties that will be addressed within NIST-CORE.

THRUST 2 - DATA STANDARDIZATION, USER REQUIREMENTS, AND MANAGEMENT TOOLS

Thrust 2 will develop a standardized data ontology, a robust data architecture and effective data management tools to support the computational environment. Thrust 1 encompasses multiple domains of science and it is therefore critical to first understand all user needs prior to data standardization. Existing ontology, data types and data formats for communities and stakeholders will be integrated into the data standards for NIST-CORE. Finally, the data architecture and data management tools will be customized to help users ingest, manage, query, visualize and share data effectively.

The existing ontology, data types, and data formats identified for the communities and stakeholders involved will be reviewed and integrated into the standards for NIST-CoE. For example, an existing earthquake loss modeling environment may have approximately 200 data types and about 10 data formats for seismic risk assessment; thus it is envisioned that as many as 500 to more than 1000 data types may be required in NIST-CORE. These will be reviewed and integrated according to the user requirements. This will utilize the extension of GML (Geospatial Markup Language) to define the data types and metadata of the datasets.

The core component of the data architecture will be the NIST-CORE data middleware layer, the place where the processing/curation of data occurs. In other words, the raw data, such as hazards, fragility curves for infrastructure, structure inventory, utility network, socio-economic data, etc., will be curated according to the data ontology, data types and data formats developed as described above. This layer has four components: 1) metadata extraction, 2) format conversion, 3) user curation, and 4) data publishing. The metadata extraction component automatically captures/processes the metadata from the raw data according to the data ontology. The format conversion provides the conversion service of the data format with information about data loss from the conversion. The user curation component then allows users to finalize the curation process with extracted metadata. Finally, the curated data will be published to the NDS. The curated data from the middleware layer will be stored in distributed data repositories. The data repositories will have secure access control allowing user(s) to have private repositories, if needed for security reasons.

Defining Resiliency Baselines, Resilience Metrics for Recovery, and Performance Improvements in Resiliency

A critical element in the impact-recovery model is the recognition that *resiliency planning and actions* can have direct consequences on physical impacts and social consequences, as well as influencing the nature and speed of recovery. The adoption of comprehensive mitigation policies (e.g., building codes and effective land-use planning) can reduce physical vulnerabilities and exposure, ensuring that buildings are kept out of high hazard areas or that buildings constructed there are better able to meet potential risks. Recovery planning can help ensure that rebuilding and repair lessens preexisting vulnerabilities, expedites debris removal, ensures capitalization of post disaster public sector activities, addresses vulnerable population needs and lessens post-disaster risks. The NIST-CORE environment, as a comprehensive community decision support tool, will address broad based resilience planning activities by helping communities understand 1) their baseline levels of resilience in relation to existing vulnerabilities and potential impacts, 2) associated recovery outcomes, and 3) resilience enhancements through the adoption and implementation of policies during recovery or as a function of resilience planning.

To capture direct and cascading impacts, the linkage between direct physical damage to the built environment (buildings and infrastructure) and broader socio-economic impacts will be refined to capture and specify damage to housing in its various forms (owner vs rental, single family, duplexes, multi-family and concomitant loss of housing units), to businesses, and to critical facilities. The focus is initially translating direct physical damage to structures and infrastructure systems to the associated disruptions caused by dependencies of social systems on the built environment. Additionally, social impacts and cascading effects for a set of hazards of varying levels and intensities will be modeled. Resilience metrics will assess impacts in the form of the loss of different forms of housing, loss and disruption of various forms of businesses, critical facilities (health, and institutional entities (hospitals, education, childcare, etc.), These in turn will be employed to model further social consequences related to population dislocations, food and health security, etc. The consequences of disaster impact for each sector cannot be defined based on a single metric (damage state(s), life safety, economic loss, etc.) or value due to differences in initial conditions, community expectations, and unequal consequences. Thus, within the NIST-CoE, an impact-performance matrix will be developed for building, infrastructure systems, and social systems, for a number of hazards.

While recovery is still one of the most understudied areas in disaster research (NRC 2006; Peacock et al. 2008; McAllister 2013), recent years have seen new research on long-term recovery and modeling approaches based on empirical and expert knowledge (e.g., Chang et al. 2014; Peacock et al, 2014). Drawing on these findings and research undertaken by the NIST team, the CoE is developing a series of algorithms that will model recovery trajectories for infrastructure, housing, businesses, and populations. They will consider not only technical aspects of repair, replacement, lifecycle and interdependence, but also broader socio-economic factors and policies that can influence recovery. The results will provide recovery-timing assessment for various sectors and sub-populations, the overall community, and a reassessment of vulnerabilities and risk given the new post disaster end-state. A goal will be to parameterize models assessing recovery under scenarios such as *expedited recovery* without policy changes or *policy driven recovery* based on recovery and mitigation planning policies.

As part of comprehensive resiliency planning, activities stakeholders may undertake performance improvement analysis as part of a recovery scenario or simply to reflect the adoption and implementation of new resiliency policies by their community or sector. The NIST-CORE environment will model performance changes (both increases and decreases) given changes or modifications in codes, standards, and policies relative to the baseline resiliency impact-performance matrix. It will be critical that the modeling environment be flexible to adapt to user, stakeholder, and community defined scenarios to allow communities to consider alternative solutions and various scenarios, such as *business as usual*, *progressive intervention*, or some other scenario. Furthermore, a long-term goal will be forecasting scenarios capturing *what-if-outcomes* given specific policy changes and *how-to* scenarios whereby stakeholders establish a resilience goal (i.e., reduced damage probabilities or recovery rates) and the model will offer optimal resiliency changes (mitigation investments, policies, etc.) needed to reach goals. This will allow users to understand the effect of changing one performance metric in the grand scheme and allow performance metrics to be refined and selected. To test this approach, numerous simulations and sensitivity studies will be performed.

THRUST 3 - SENSITIVITY, VALIDATIONS, AND FIELD STUDIES

Investment Optimization and Decision Algorithms

Considerable research has been conducted on the topological analysis and optimal flow of single networks (Newman et al. 2006). On the other hand, the mathematical modeling and optimization of interdependent networks – a fundamental component of community resilience –is relatively new. A key distinction between the two paradigms is that a network component identified as minor importance from the perspective of an isolated network may be critical when the network is considered from an interdependent framework. Failures of links or nodes in interdependent networks may lead to cascading effects and system-wide failure. Variation in the failed links or nodes will affect the speed at which a community recovers from a disaster as well as the extent of recovery. The size and complexity of a community-level model require novel algorithmic approaches that produce accurate solutions efficiently. Intelligent search algorithms based on meta-heuristics are being developed and applied to effectively search the solution space (defined by classical modeling techniques), identify critical interdependent components, develop strategies to reduce time to recovery, and determine near-optimal network designs which improve community resilience. These algorithms are being incorporated into NIST-CORE.

Engineering and economic investments to improve community resilience are being evaluated against a no-action (*laissez faire*) benchmark. More specific, investment expenditures meant to boost resilience to hazard shocks involve reallocation of resources away from *normal* expenditures in the economy. The net short-run economic impact of reallocating resources is negative. However, insofar as these investments are resiliency-enhancing, they will function to mute initial losses (*robustness*) and speed return to pre-shock equilibrium (*rapidity*), thus enhancing *resourcefulness* going forward (Bruneau et al 2003). The negative short-term costs of investments, both direct and indirect (from system efficiency losses), will be compared to the long-term losses averted by community resilience for various investment options as part of this optimization.

To summarize, NIST-CORE will model how a natural hazard impacts the functioning of commercial and residential buildings, transportation, utilities (water), telecommunications and energy. A Computable General Equilibrium (CGE) model will be used to estimate the economic impact of all these effects. The CGE model can estimate the initial downturn in the economy and also estimate the economic resilience of the economy depending on the resilience of the five engineering scenarios. Alternative mitigation policies that can reduce the impact of the hazard with a focus on the costs and benefits of each policy will be developed.

Infrastructure Evaluations

NIST-CORE will be evaluated for individual infrastructure systems (e.g., buildings, transportation), coupled infrastructure systems (e.g., power-water, power-buildings-water), and the fully coupled model (all components including economics and social structures). Observations from Hurricane Ike will be used to validate the individual system models. Hurricane Ike is particularly suitable for this because damages were confined to a relatively small region (Houston, Galveston). For initial validation of the fully coupled system, observations and data from both the Northridge earthquake and Hurricane Ike will be used.

NIST-CORE Architecture and Ontology Validation Studies

Data for Hurricanes Ike and the Northridge earthquake will be used to perform beta testing approximately every 4 to 6 months as the full NIST-CORE architecture is being developed during Year 2 and into Year 3 of the Center. This will allow a systematic validation of each of the integration steps for databases, open source environment communication, search algorithms, and investment optimization. Validation of the NIST-CORE computational environment architecture and forecasts of risk and community resilience based on available computational models and supporting databases will contain significant unavoidable uncertainties. In any application of NIST-CORE (validation or forecasting), the question of paramount importance is whether the models and databases embedded (or interfaced) in it are sufficient to assess infrastructure risk or forecast community resilience with a level of accuracy (or confidence) sufficient for rational decision-making. Within NIST-CORE this critical research challenge is being addressed by structuring the decision analysis module within the environment within a machine learning shell that will enable NIST-CORE to “learn” from the data provided to it, recognizing specific patterns or capturing statistical characteristics during the course of the resilience forecast, and advising the analyst or the decision-maker as to whether the forecasts are likely to be useful.

Field Studies

Field studies will be conducted to enable validation of NIST-CORE for individual systems, interdependencies and cascading effects if present, and the fully integrated data architecture. Mid-term (30 days to 6 months) and long-term field studies will help validate NIST-CORE accuracy in computing recovery trajectory. Data will be collected to characterize the hazard, damage to infrastructure and social systems, and recovery by the community.

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