A Guide to Develop Community Resilience Performance Goals and Assessment Metrics for Decision Making

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ABSTRACT: The National Institute of Standards and Technology (NIST) is conducting outreach and research to develop a Community Resilience Planning Guide for Buildings and Infrastructure Systems and quantitative science-based assessment tools and metrics for community resilience. The research focuses on the performance and rapid recovery of the built environment to a functional level for significant hazard events, and the associated technical and social challenges. Major objectives include the development of a community-level methodology based on performance goals, quantitative science-based resilience assessment tools and metrics based on reliability and risk analysis, and guidance and pre-standard documents that can be adopted by communities and code and standard bodies to support rational public policies for mitigating risk to communities. Science-based decision support tools and metrics are needed to help communities evaluate the performance of built systems that support social and economic functions in a community and assess alternative plans and associated risks. The immediate need for community resilience tools for the built environment is being addressed by NIST through a planning methodology and implementation guidance that includes a process for setting community performance goals and evaluating recovery through time to return of functionality. Quantitative science-based assessment tools and metrics for community resilience, based on reliability and risk principles for integrated 'system of systems' modeling, are in early stages of development. Researchers are developing quantitative models of individual infrastructure systems, but much remains to be done before an integrated systems model that incorporates uncertainties in data and system condition is available and validated. The addition of community performance goals, multiple hazard levels, and recovery of functionality to the traditional elements of mitigation, performance and damage levels, and losses and consequences provides a more complete risk-informed assessment of community resilience. NIST outreach and research activities that address these issues are summarized, and a simple risk formulation for resilience that incorporates recovery is proposed.

1. INTRODUCTION

The risk for substantial damage and disruption to communities across the United States due to hazard events continues to increase, due in part to the combined effects of urban development and population growth (NOAA 2005, NRC 2006). Physical infrastructure is regularly subjected to a range of natural hazards (e.g., winds and flooding along coastlines, wildfires in the wildland-urban interface, tornadoes in the midwest, and seismic events in earthquake-prone regions). Additionally, much of the infrastructure is increasingly vulnerable due to aging effects and a diminishing capacity to resist hazards.

Disaster events often result in loss of life, disruption of social, commercial, and financial networks, and destruction of property, sometimes severe enough to result in significant changes and diminishment of communities. Total losses can exceed $100 billion in large disaster events. For example, the wind and storm surge during Hurricane Katrina in 2005 caused extensive damage across several states (NIST 2006). Beyond the storm surge, the winds damaged industrial facilities, oil storage tanks, and the power distribution system. Insured losses for Hurricane Katrina in 2005 were $44 billion, and total economic (non-insured) damages were estimated to exceed $200 billion (King 2005, 2008). More recently, Japan had a cascading disaster of earthquake, tsunami, and nuclear power plant crises. The World Bank estimated that the reconstruction costs for this disaster will range between $122 and $235 billion (Nakamura 2011).

Communities rely on buildings, facilities, and infrastructure systems to provide shelter and support business, government, industry, and other vital services for community prosperity and health. Community resilience addresses the ability of communities, which includes their social systems and physical infrastructure, or built environment, to withstand and recover rapidly from hazard events and to minimize significant disruptions. Many communities recognize significant hazards that may threaten their safety and wellbeing, and address community vulnerabilities through preparedness, mitigation, and design efforts to minimize their risk of damage and losses. These are important and vital steps for all communities. However, across the nation, communities have continued to experience significant damage and losses, even those with robust codes and standards adoption and enforcement.

2. OTHER RESILIENCE ACTIVITIES

There are a number of resilience initiatives and activities at regional, national, and international levels, including assessment methodologies that engage stakeholders in a variety of ways. Resilience initiatives focused on the United States include the San Francisco Planning and Urban Research Association (SPUR 2009) Framework, Baseline Resilience Indicators for Communities (BRIC, Cutter et al 2014), the Community and Regional Resilience Institute's (CARRI) Community Resilience System (2013), the Oregon Resilience Plan (2013), NOAA's Coastal Resilience Index (2010), and the Communities Advancing Resilience Toolkit (CART, Pfefferbaum et al 2013). International initiatives include the United Nations International Strategy for Disaster Reduction (UNIDSR 2014) Resilience Scorecard and the Rockefeller Foundation's 100 Resilient Cities initiative (Rockefeller 2014).

Some approaches propose qualitative methodologies, such as checklists with subjective scoring, while others use quantitative approaches that present resilience measures or summaries in the form of scorecards or dashboards. In general, most of these methodologies focus on social issues, and in some cases, the focus is in one particular social service or system. Without accepted resilience metrics, these methods provide a starting point for communities to conduct overall assessments.

NIST found that most of these resilience initiatives have minimal integration of infrastructure systems and how they support social and economic needs, and do not address dependencies between and among the social and built environments. The NIST Community Resilience Planning Guide for Buildings and Infrastructure Systems addresses this issue.

3. NIST COMMUNITY RESILIENCE PROGRAM

In response to a national need for resilience in communities, NIST established the Community Resilience Program in 2013, and awarded the Community Resilience Center of Excellence to Colorado State University and ten other institutions in February 2015. The NIST Community Resilience Program focuses on the role of the built environment in improving community resilience, and establishing performance goals informed by social needs and institutions. Current best practices, codes and standards primarily address life safety issues for buildings, reliability of utility service during normal operation, and aspects of community preparedness and immediate response to disruptive events. However, they do not address the integrated performance and reliability of buildings and infrastructure systems at the community level, dependencies between or among social and physical systems, or plan for recovery of function across the community. The lack of decision making support tools to help communities evaluate the performance of their social and built systems is the basis for the NIST Program. Communities need science-based tools that allow customized development and evaluation of alternative plans and associated risks for their integrated systems.

The NIST plan has two thrusts: (1) development of a Community Resilience Planning Guide and Implementation Guidelines to support community resilience planning and decision making, with an emphasis on systems-level performance goals and recovery metrics for functionality based on recovery time, and (2) establishment of a research program to develop quantitative science-based assessment tools and metrics for community resilience based on reliability and risk principles for integrated 'system of systems' modeling. The research plans for systems modeling includes significant interaction with the NIST-sponsored Community Resilience Center of Excellence (CoE).

NIST and CoE researchers will collaborate to conduct community-level research and analyses of how social systems are supported by the built environment and develop tools to support community resilience assessment and metrics for the built environment and its impact on social systems. The CoE has three objectives:

- Develop an integrated, multi-scale, computational modeling environment for community systems to support development of new standards and tools for assessment and decision making.
- Foster the development of data architectures and data management tools to enable disaster resilience planning.
- Conduct studies to validate resilience data architectures, data management tools, and models.

The decision support system will be embedded in a state-of-the-art computational environment that integrates physics-based models of buildings and other infrastructure, networks for transportation, energy, water, wastewater, and communication systems, a spectrum of hazards, models of social and economic systems, and resilience-based performance criteria and metrics.

4. COMMUNITY RESILIENCE PLANNING GUIDE AND IMPLEMENTATION GUIDELINES

A resilient community has facilities and infrastructure systems that maintain acceptable levels of functionality during and after a disruptive event and fully recover within a specified period of time. The other aspects of a resilient community—security, protection, emergency response, governance, business continuity, and social issues related to human health, safety, and general welfare—are also important, and inform the performance goals for the built environment.

It is often argued that if communities adopt and enforce current codes, standards, and regulations, that resilience will be largely addressed at the community level. This approach is followed by a number of communities, and should be, yet significant damage from hazard events still occurs. One factor is the independent development of codes, standards, and regulations for buildings, power, communication, transportation, and water/wastewater systems. Additionally, only a small fraction of the built environment is replaced with new construction each year.

The nominal service life of many buildings is taken as 50 years, and infrastructure systems may be expected to have even longer service periods. At any time, a community's built environment contains an integrated set of systems in varying stages of functionality and capacity. Addressing the issue of existing infrastructure, and its state of degradation, is a key component to understanding and measuring community resilience.

As an indicator of the risk that the built environment faces from hazard events, Presidential Disaster Declarations for the period from January 2000 to January 2011 (FEMA 2010) ranged from 45 to 81 declarations every year for floods, hurricanes, tornadoes, earthquakes, fire events, and severe storms. Many of the disaster declarations were based on economic recovery costs, despite the fact that the hazard intensity experienced during the events fell below current design thresholds. During this period resilience activities largely focused on critical infrastructure as well as mitigation for individual facilities and emergency response activities to meet social needs (McAllister 2013). This approach resulted in piecemeal protection and risk reduction, and typically did not significantly improve the resilience of the community.

The term 'resilience' has been generally defined as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NAC 2012) or, similarly, "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (PPD-21 2013). NIST has adopted the second definition for its community resilience work. Following these broad definitions, community resilience activities include disaster preparedness, mitigation, design to withstand hazards, and emergency response activities. However, additional activities are needed to achieve community resilience: development of performance goals at the community level, assessment of performance and recovery at multiple hazard levels, and planning for rapid recovery of community functionality. Inclusion of such factors provides a balanced basis for decision making, where the relative costs of alternative mitigation, performance/damage, and recovery plans are considered as a complete option. This approach was used by San Francisco and the state of Oregon for their resilience planning (SPUR 2009, Yu, Wilson, and Wang 2014)

These observations led communities and researchers to recognize a need for resilience to be addressed on a community scale. Communities have a decision-making authority to enable resilience planning, funding, and implementation, and can act as logical conveners for collaboration with private owners of facilities and utilities. Communities provide a range of services to meet social needs, which are supported through the built environment. The performance of these systems is integrated, even though they are often designed and constructed independently. Resilience of individual buildings, facilities, and infrastructure systems should be defined in terms of the role and function they serve within the community. The resilience of the built environment needs to be evaluated as a system of systems with dependencies that may affect other systems and the entire community.

To provide immediate guidance to communities, and to help define research needs, NIST is developing a Community Resilience Planning Guide and Implementation Guidelines to advance the current state of community resilience as follows:

- The Planning Guide provides guidance for developing community performance goals for functionality of the built environment based on social needs for multiple hazard levels and recovery goals based on time to restored functionality. Guidance is provided for developing goals and plans for buildings and infrastructure system as integrated community systems. The Planning Guide also identifies available codes, standards, tools, and best practices to plan for and support community resilience of the built environment. Due to the significant breadth of stakeholders required to develop this document, experts in sociology, infrastructure systems, community and emergency planning, and other supporting fields were consulted, a series of workshops were held to engage a number of stakeholders, and public comments were invited during the Planning Guide development process.
- To support the Planning Guide, Implementation Guidelines will be developed starting in 2015 to provide best practices and

real-world examples for implementation approaches. The first version of the Resilience Guidelines will address critical infrastructure and is intended to serve as a resource document of best practices.

- To support the continued development of the Planning Guide and Implementation Guidelines, a Disaster Resilience Standards Panel (DRSP) will be convened in 2015. The DRSP will be established as an independent organization for the broad range of stakeholders to address community resilience issues. Stakeholder interests include community planning, disaster recovery, emergency management, business continuity, insurance/re-insurance, state and local government, design, construction, and maintenance of infrastructure (buildings, water and wastewater, electric power, communications, transportation), and standards and code development.

The Planning Guide and Implementation Guideline development will identify existing standards, codes, guidelines, and tools that can be implemented to enhance resilience. Additionally, gaps in current standards, codes, regulations, best practices, and tools will be identified to determine research needs.

5. COMMUNITY RESILIENCE MODELING, TOOLS AND METRICS

Community resilience promotes the integrated functionality of complex physical systems. Facilities and systems that are essential to a community, especially during and after extreme events, need to remain functional after a disruptive event. Other systems may have reduced performance requirements depending on their role in the community. Such decisions should be informed by reliability and risk-based tools for assessment of alternative strategies at the community level.

Risk assessment for disaster resilience should include all consequences, including recovery costs due to damage for a given hazard event. Typically, consequences are expressed in terms of the probability of losses due to damage

$$P[L] = P[L|D]\, P[D|H]\, P[H] \tag{1}$$

where $P[H]$ is the probability of a hazard event, $P[D|H]$ is the conditional probability of damage given the hazard event, and $P[L|D]$ is the conditional probability of losses given the damage level. To support resilience assessments, consequences should also include recovery costs

$$P[R] = P[R|D]\, P[D|H]\, P[H] \tag{2}$$

where $P[R|D]$ is the conditional probability of recovery costs given the damage level. At present, costs cited after events are insured costs which address only part of the recovery costs expended by communities.

This simple formulation demonstrates the need for the following data and models that are not available or well developed for community level assessments:

- Community level performance goals for each physical infrastructure systems based on social needs and dependencies in the integrated community system.
- A rational basis for selecting multiple hazard levels to allow sensitivity studies of community resilience over a range of demands.
- Quantitative reliability-based representations of infrastructure systems and components that include aging and deterioration effects on existing infrastructure performance.
- Models that capture the physical performance and service provided by each infrastructure system in a community, including uncertainties in input data, system conditions, and modeling methods.
- Models that address social and economic factors to facilitate decision making.
- Models that address recovery based on damage levels and available resources.

- Integrated models of system dependencies and cascading effects of one system failure on other systems, including uncertainties.
- Data for validation of models, particularly recovery data.
- Criteria for determining when model results have adequate confidence intervals for decision making.

Significant research tasks are associated with integrated models for infrastructure systems. The models, data, and performance criteria can be quite different for each infrastructure, social, or economic system. For instance, social impact models may be agent-based or system dynamics, economic models may be based on empirical/statistical data, power systems may use network models, and buildings may have fragility representations. Methods for simulating dependencies or cascading effects between these models are not readily available.

As robust models for studies of community resilience are developed, a scientific basis for tools and metrics will be established to help communities with their decision making and assessments. The NIST research program and Community Resilience Center of Excellence will continue to define the research needs as system models are developed and advanced for community resilience.

6. CONCLUSIONS

The lack of decision making support tools to help communities evaluate the performance of their social and built systems is a major constraint to effective resilience planning at the local level. Communities need science-based tools and metrics that allow assessment of alternative plans and associated risks for their integrated systems.

The NIST research plan is addressing the immediate need for community resilience tools for the built environment by developing a methodology and implementation guidance. The inclusion of community performance goals provides needed context to resilience goals for individual buildings and infrastructure systems within the community. The evaluation of recovery through time to return of functionality serves as an interim step for a complete assessment of consequences.

The need for quantitative science-based assessment tools and metrics for community resilience based on reliability and risk principles for integrated 'system of systems' modeling is in its beginning stages.

To advance community resilience beyond its current state, reliability and risk-based assessment tools at the community level are needed. Researchers are working to develop quantitative models of individual infrastructure systems, but much remains to be done before an integrated systems model that incorporates uncertainties in data and system conditions is available and validated. The addition of community performance goals, multiple hazard levels, and recovery of functionality with the traditional disaster planning activities of mitigation, design for performance, and assessment of consequences and losses will provide a complete evaluation of risk.

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