Validating Interdependent Community Resilience Modeling using Hindcasting

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ABSTRACT: The resilience of communities prone to natural hazards can be enhanced through the use of risk-informed decision-making tools. These tools can provide community decision-makers key information, allowing them to consider an array of mitigation and/or recovery strategies. To comprehensively assess community resilience, all sectors that have an influence, including physical infrastructure (buildings, bridges, electric power networks, etc.) and the socio-economic systems should be considered. For this purpose, the Center for Risk-Based Community Resilience Planning (hereon referred to as the Center), headquartered at Colorado State University in Fort Collins, Colorado, USA, developed an **I**nterdependent **N**etworked **CO**mmunity **R**esilience modeling **E**nvironment (IN-CORE) capable of simulating the effects of different natural hazards including tornadoes, earthquakes, tsunamis, among others, on physical and socio-economic sectors of a community while accounting for interdependencies between the various sectors. However, such a complex computational environment must be validated with each model being verified as a single component or sub-system. Within the Center, models are verified for accuracy as they are developed, but the combination of all the models must be verified for accuracy and then validated to ensure that it provides the desired output with the accuracy needed for risk-informed decisions. The community of Joplin Missouri in the United States was hit by an EF-5 tornado on May 22, 2011. In this paper, the city of Joplin is modeled in IN-CORE to estimate the building and electrical power network damage, economic disruption and recovery, infrastructure repair and recovery through several metrics, as well as population dislocation. Results are compared with best estimates obtained from collected post-event data, interpreted existing government documentation, and archived literature related to Joplin.

1. BACKGROUND

In 2015, the National Institute of Standards and Technology (NIST) funded the Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University with 11 partnering institutions to collaborate with NIST on community resilience research. Three areas where the cooperative agreement seeks to contribute to technical advances are: (1) a modular, open-source computational framework known as IN-CORE (Interdependent Networked Community Resilience) which will allow researchers the ability to model interdependent physical-socio-economic response and recovery to natural hazards such as earthquake, tsunamis, floods, and tornadoes. Risk relates to predicting the potential of losses, whether monetary, safety-related, or other; but resilience focuses on preparation and recovery of a community including informing decision-makers of near-optimal policies (Koliou et al, 2018) and decision levers which can be utilized during the planning stages and recovery process.; (2) data requirements for multidisciplinary modeling of communities including data structure for the computational environment IN-CORE; and (3) validation of the modeling processes, their interactions, and the data structure through field studies and hindcasting.

Hindcasting is the procedure of analyzing a past event without using any knowledge that became available during or after the event. It requires careful consideration by all analysts to keep the results as pure as possible and allow for validation. The ability to hindcast is limited to objective and quantitative models which are explained later in this paper, since an analyst cannot forget what they know. In this paper, a hindcast of the Enhanced Fujita (EF) 5 double-vortex tornado that struck the U.S. city of Joplin, Missouri in 2011 is presented. Four analyses are presented at their varying levels of maturing/completion including (1) building damage prediction using 19 recently developed archetypes by Memari et al (2018) with four associated damage fragilities for each archetype which includes building functionality and direct losses; (2) coupled buildings with electrical power network (EPN) outages; (3) economic disruption using a computable general equilibrium model; and (4) a brief discussion of household dislocation predictions as a function of wind speed experience by buildings based on 1992 Hurricane Andrew data (Peacock et al, 2012).

Tornadoes occur regularly in the U.S. with geographically small strike areas but can result in high casualty rates and billions of dollars in economic loss. The resilience (ability to absorb impacts and recover rapidly from hazards) of communities to tornadoes can be enhanced through the use of risk-informed decision-making tools. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, developed a beta version of the IN-CORE computational environment. The developed computational environment is capable of simulating the effects of different natural hazards including tornadoes on the physical and socio-economic sectors of a community, as well as accounting for select interdependencies between the sectors. In this study, the beta version of IN-CORE was used to assess the damage caused by tornadoes to buildings in Joplin, Missouri. One of the important aspects of IN-CORE is the use of physics-based (developed by numerical simulations rather than being empirically derived) models. Although numerical simulations are valuable, these models need to be verified. In order to verify damage assessment of a community subjected to tornadoes, damages caused by the EF-5 tornado (rated based on the Enhanced Fujita tornado intensity scale (McDonald and Mehta, 2006)), which struck the city of Joplin Missouri, U.S.A. on May 22nd, 2011, were estimated in this study. The 2011 Joplin tornado resulted in 161 fatalities, approximately 1,371 injuries and more than $2.8 billion in physical damage, making it the deadliest and costliest single tornado in the country since 1947 (FEMA, 2011). It is worth mentioning that in 1947, Doppler radars did not exist and the ability to warn those in the path of tornados was essentially nonexistent. The Joplin tornado was one of the estimated 1,691 tornadoes that occurred in the United States in 2011 (NWS, 2011) but due to the severity of the damaged caused by this tornado, it has been widely studied by researchers (e.g., Coulbourne and Miller, 2012, Prevatt et al., 2012) and is utilized in this study to validate the IN-CORE tornado damage predictive models. Figure 1 shows the tornado path with red cross hatching closest to the center-line representing the wind speed within the vortex that was estimated to have EF5 wind speeds (>320 km/h (>200 mph)), reducing to yellow for EF4 wind speeds and as the cross hatched areas move laterally outward from the tornado path eventually reaching EF1 rating as light blue.

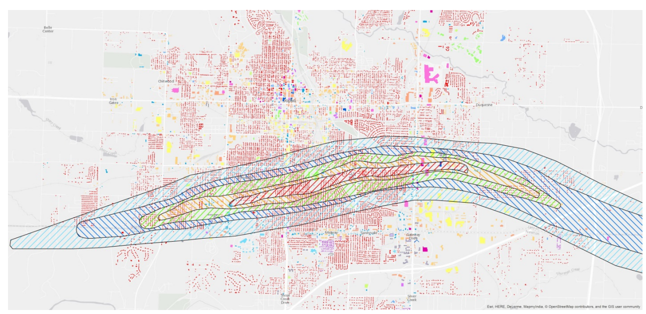

Figure 1: The 2011 Joplin tornado path and building footprints; each color indicates a different building archetype with red=residential; yellow=commercial; and 17 others less prevalent.

2. MODELING BUILDING DAMAGE, FUNCTIONALITY, AND DIRECT FINANCIAL LOSS

The functionality methodology of this study focuses on generating repair time fragility curves accounting for the structural and non-structural component performance, without accounting for external interacting systems (e.g. lifelines and service personnel) and integrates the basic principles of performance-based engineering (Koliou and van de Lindt 2018). This is a systems' based approach without being influenced by repair time delays due to external parameters, which occur at the system-of systems modeling process level. It is recommended in this study that certain functionality levels (e.g., 100%, 75%, 50, and 25% functionality) are associated with damage combined for structural and non-structural building components. The functionality levels are structure/building type dependent since each building type consists of different structural and non-structural components that affect its functionality and use by the occupants. The proposed methodology is comprised of four steps. The first three steps focus on generating component/sub-assembly functionality/repair time fragility curves by integrating basic principles of Performance Based Engineering (Step 1) combined with repair characterization analyses (Step 2). At the final step of the methodology (Step 4), the functionality fragilities of the different structural (e.g., walls, frames etc.) and non-structural (e.g., windows, doors etc.) components comprising a typical building are combined through a set of probabilistic simulations to generate the building (system level) repair fragility curves for various levels of functionality. An example of a functionality fragility curve for achieving functionality levels (Q) equal to 100% for various damage states is shown in Figure 2 for a typical residential building archetype (where DM is the damage measure, or damage state). A DM/DS 4 indicates the structure is destroyed and needs replacement.

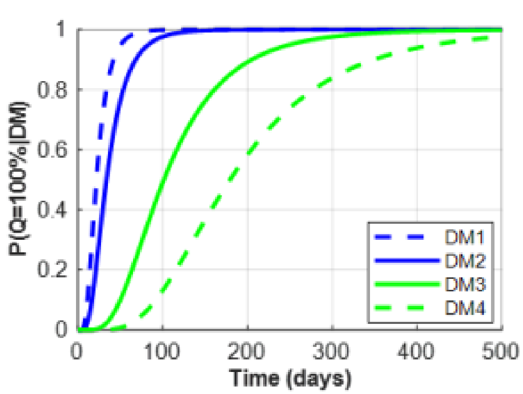

Figure 2: Functionality (repair time) fragility curves for reaching Q= 100% for T4 (residential) archetype

Determining community level physical damage (see Memari et al, 2018) was used to eventually determine the loss which was broken down into a three-phase process. Spatial damage is shown as a probability of reaching DS3 in Figure 3 for the footprint of the Joplin tornado. The first phase in estimating the loss was to determine loss values, with probabilities, from a building's damage state. These initial loss values only included building subassembly items that were initially determined in the assumed construction of a building archetype; namely the Main Wind Force Resisting Systems (MWFRS) and Components and Cladding (C&C). Interior items such as, plumbing, electrical, stairs, interior walls, and similar items, were therefore left out of the analysis for this phase. Phase two uses FEMA's HAZUS (Federal Emergency Management Agency, 2009) archetype building subassembly values (walls, roof, roofing, interior walls, stairs, foundation, and more) as a percent of the total building value. A percent of total building value was then attributed to the subassembly items that were included in the damage state fragilities, leaving the remaining non-structural (or interior) items, which were determined as the remaining percent of total value. The third phase consisted of determining the content value, which was considered to be an additional value to the structure. Some archetypes, such as hospitals, may have over 200% additional to the building's value in contents, while others may have an additional 50%, such as the standard residential structure. At this point, only archetype total economic values were determined along with the loss fragilities based on the damage state fragilities. Determining the loss from the second and third phases required the percent of roof lost by the damage state of the building. The FEMA's HAZUS equations for roof loss as relation to interior value were used to determine the loss value for the remaining nonstructural items and contents (Federal Emergency Management Agency, 2009). These equations were based on the knowledge that, in wind events, damage to the interior is mostly tied to whether or not wind is able to penetrate the building. Once the losses from phases two and three were determined, these were then combined with the fragility-based losses to estimate the overall loss value for a structure as a ratio of the total building archetype value (Pilkington et al, 2018).

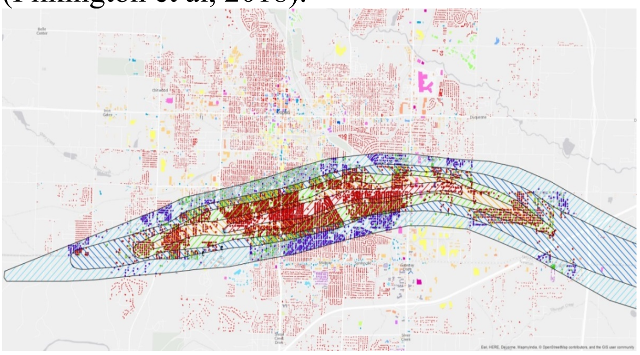

Figure 3: Probabilities of being in damage state 3 with red approaching unity and blue and green approaching zero, i.e. similar to a heat map

3. COUPLING BUILDINGS AND EPN

To account for the damages to transmission lines in the power loss estimation process, an analysis was performed for distribution lines and their transmission lines. Using the fragility curves developed by Fenton and Sutherland (2011) for transmission towers, the analysis showed that an average of 130 transmission towers would fail for this tornado, which is relatively close to what was observed (135 transmission towers failure reported by NIST, (NIST, 2014)). Most of the transmission lines in the tornado path were connected into a particular substation, S9, therefore it is reasonable to assume that this substation lost power. Also, substations S2 and S5-S8 were connected only to one 69kV line and the electrical power for this line came from three substations, namely S3, S4 and S9, which were connected to (directly or indirectly) 161 kV lines. Determining electrical power percentage, provided by each of these three substations depends on the details of the electrical power network set by the electrical power company (Attary et al., 2018). However, in this analysis, to approximately account for this dependency, it is assumed that the electrical power provided to the five mentioned substations (S2 and S5-S8) is evenly distributed between the three substations (S3, S4 and S9). Therefore it was estimated that, by losing the connection to substation S9, 1/3 of the electrical power required for substations S2 and S5-S8 would be lost. As a result, 0.33 probability of power loss has been assigned to these five substations and was propagated through to the customers. Overall, results were found to compare well with reports of power outages and NIST (2014).

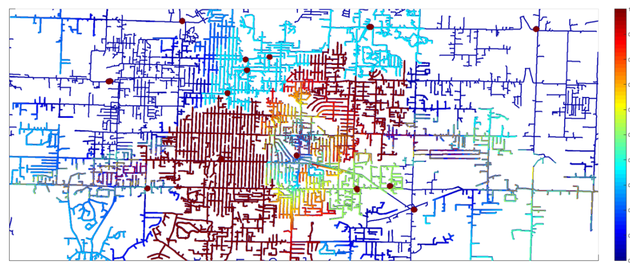

Figure 4: Probability of power loss (as shown in legend) considering substation damage and damage to transmission lines

4. ECONOMIC MODELING

A computable general equilibrium (CGE) approach combines an extensive data collection effort that is merged with a model based on fundamental economic principles. Data is collected and organized into a social accounting matrix (SAM), which reflects the interaction of households, firms, and the relevant government entity as they contribute to economic activity. The SAM is inserted into a CGE model that is based on (1) utility-maximizing households that supply labor and capital, using the proceeds to pay for goods and services (both locally produced and imported) and taxes; (2) the production sector, with perfectly competitive, profit-maximizing firms using intermediate inputs, capital, land and labor to produce goods and services for both domestic consumption and export; (3) the government sector that collects taxes and uses tax revenues in order to finance the provision of public services; and (4) the rest of the world.

A CGE model is calibrated when it can reproduce the base data in the SAM. This implies that the CGE model is a good representation of the economy and how the economy responds to a wide range of economic shocks can be simulated.

A CGE model for Joplin was constructed using 2010 data with the objective of modeling how the Joplin economy responded to the 2011 tornado. A computer simulated tornado model representing the actual tornado was used and shocked the developed CGE model to predict how the Joplin economy responded. If one accounts for the insurance money that entered the economy immediately following the tornado, the CGE model can be compared to actual household income for 2011 and 2012. The forecast error was -7.1% for 2011 and 0.7% for 2012. For the longer run, the CGE model performed well and there are current studies focusing on improving the forecast accuracy for the year of the natural disaster. In related work, the economic impact of waiting a year before insurance money or federal funding is injected into the economy was also examined. Waiting a year for outside funding after the tornado resulted in a loss of real household income of 3.5%. The economic costs of waiting for outside funding after a natural disaster can be significant.

5. POPULATION DISLOCATION

Population dislocation modeling has not been completed, but basic fragility curves were developed as a function of wind speed by Clapp (2017) using data from Peacock et al (2012). Figure 5 presents these basic fragility curves which do not account for socio-economic demographics or other important factors yet, but will be further developed. Future research efforts will use the Joplin data to validate population dislocation models using output from the building damage, coupled EPN, and economic CGE models. The linked models will provide an opportunity to compare fragility curves and existing logistic regression models at the household level.

6. IMPLEMENTATION IN IN-CORE

The Joplin Hindcasting has been implemented using IN-CORE. IN-CORE v1.0 is a Java application with a plug-in based architecture that builds upon the Ergo[1] Framework and allows researchers to extend IN-CORE's capabilities through the addition of new science/features. These features can be connected with the existing 40+ analyses to produce new scientific results. The core technologies of the Ergo framework include Eclipse Rich Client Platform (RCP)[2], Geotools[3], Visualization Toolkit (VTK)[4], JFreeChart[5], and Jasper reports[6], etc, as depicted in Figure 6. These technologies make up the core of Ergo and provide capabilities such as data management, visualization, analysis, etc. The Eclipse RCP framework allows IN-CORE to be extensible via the Open Services Gateway Initiative (OSGi) specification, which describes a modular system and a service platform for the Java programming language that allows applications to be extended by incorporating new bundles that add or enhance capabilities of the platform. Eclipse builds on this through the concept of extensions to contribute functionality to a certain type of Application Programming Interface (API) defined by a plug-in through an extension point. A plug-in defines a contract or API with the definition of an extension point. This allows other plug-ins (bundles) to add contributions (extensions) to the extension point. For example, it is through this mechanism that a new extension for Tornado building damage was defined for IN-CORE using the "edu.illinois.ncsa.ergo.core.analysis.newAnalyses" extension point and a new data type for the tornado hazard was added to the

[1] http://ergo.ncsa.illinois.edu/
[2] http://www.eclipse.org/
[3] http://geotools.org/
[4] https://www.vtk.org/
[5] http://www.jfree.org/jfreechart/
[6] https://community.jaspersoft.com/project/jasperreports-library

"edu.illinois.ncsa.gis.gisSchemas" extension point to describe the Joplin Tornado path.

Two major analyses were implemented on the platform. First, the Tornado building damage analysis was implemented in INCORE-v1 as a set of Java Plugins. The analysis takes as input a building dataset and tornado hazard shapefiles representing the Joplin tornado path, and building fragility curves. For each building, IN-CORE identifies if a building was within the tornado path and then finds the EF boundary using Geotools to determine if the building point is within the polygon. Using this information, IN-CORE computes the wind speed using a uniform random distribution. Based on each building's attributes, IN-CORE selects the fragility for the corresponding structure and computes the expected damage, which can be visualized.

Joplin Tornado EPN analysis performs the calculation of average damage for transmission towers and distribution poles by using the cellular automata technology that defines the service area grows from the 14 substations through the network and convert area as probability map. Based on the service areas, it performs the recovery analysis with different time steps such as 24 hours, 24 - 48 hours, and after 72 hours. The power loss probability is then assigned to each building as described earlier.

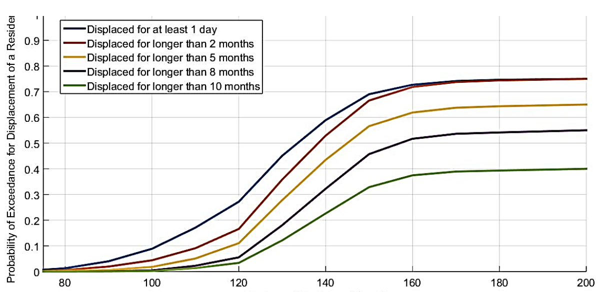

Figure 5: Fragilities for duration of dislocation as a function of wind speed experienced by the household/building

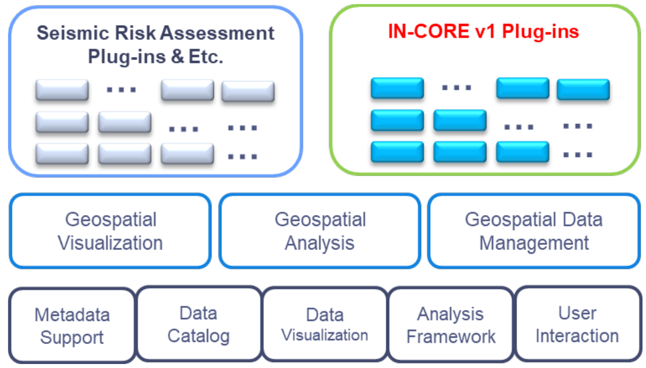

Figure 6: Schematic showing the architecture of IN-CORE v1.0

7. CLOSURE AND NEXT STEPS

Hindcasting is critical to be able to determine the accuracy of predictive algorithms used within In-CORE. In this case, the early focus was on damage to physical systems and is now turning to modeling recovery.

Efforts are underway to comprehensively document the recovery of Joplin over the last seven years in order to compare spatial and temporal recovery of physical infrastructure and the socio-economic systems they support.

8. ACKNOWLEDGMENTS

Funding for this study was provided as part of Cooperative Agreement 70NANB15H044 between the National Institute of Standards and Technology (NIST) and Colorado State University. The content expressed in this paper are the views of the authors and do not necessarily represent the opinions or views of NIST or the U.S Department of Commerce. Researchers who helped with gathering data during the field trip to the city of Joplin are acknowledged.

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