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THE INTERDEPENDENT NETWORKED COMMUNITY RESILIENCE MODELING ENVIRONMENT (IN-CORE)

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ABSTRACT

The National Institute of Standards and Technology (NIST) funded the multi-university five-year Center of Excellence for Risk-Based Community Resilience Planning (CoE), headquartered at Colorado State University, to develop the measurement science to support community resilience assessment. Measurement science is implemented in a computational environment with fully integrated supporting databases to model the impact of natural hazards on communities including recovery, evaluate the key attributes that make communities resilient, and optimize resilience enhancement/planning strategies. The Interdependent Networked Community Resilience Modeling Environment (abbreviated as IN-CORE) is built upon the MAEViz/Ergo software. Version 1 of IN-CORE (i.e., IN-CORE 1.0) allows the modeling of the performance of (inter)dependent physical infrastructure when subject to natural hazards, as well their recovery. Social systems are also considered using state-of-the-research models, while economic impacts are assessed using computable generalized equilibrium (CGE) models, thus forming a nexus of physical, social, and economic domains. Version 2 of IN-CORE (i.e., IN-CORE 2.0) will include hurricanes, coastal storm surge and riverine flooding, as well as multi-hazard events, and will optimize a combination of public and private investment strategies prior to and/or after an event with the goal of improving community resilience as quantified by the resilience metrics identified by the CoE. This paper provides an overview of IN-CORE 1.0 and touches on some of the modeling features in IN-CORE 2.0, which is scheduled for release in 2019.

Keywords: Natural hazards; Resilience; Recovery; Infrastructure; Economic impacts; Social impact

1. INTRODUCTION

Community resilience depends on the performance of the built environment and on supporting social, economic, and public institutions that, individually and collectively, are essential for immediate response and long-term recovery of a community following a damaging hazard event. The resilience goals of a community are based on social needs and objectives that are specific to its character – its prior experience with natural hazards, the vulnerability of the population, economic and financial drivers and resources, and local building regulations and construction practices. The performance of the built environment in the United States, which is a key factor in community resilience, is largely determined

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by codes and standards, which are applicable to individual facilities and have the primary objective of preserving life safety under design-level hazard events. However, current codes do not address facility performance in the period of recovery following an event. Moreover, design of (inter)dependent transportation systems, utilities (e.g., potable water, wastewater and electric power) and communication systems currently is based on criteria developed by independent professional organizations or industry sectors with different performance objectives and design hazard levels. In the current environment, there is no assurance that all systems required for community resilience will perform at a consistent level during and following a hazard. Furthermore, science-based measurement tools to evaluate performance and resilience at the community scales, 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 National Institute of Standards and Technology (NIST) funded the multi-university five-year Center of Excellence for Risk-Based Community Resilience Planning (CoE) with the purpose of developing a computational environment with fully integrated supporting databases to model the impact of natural hazards on communities as well as their recovery, evaluate the key attributes that make communities resilient, and optimize resilience enhancement/planning strategies. The center is headquartered at Colorado State University and includes experts in resilience from the University of Illinois at Urbana-Champaign, University of Oklahoma, University of South Alabama, University of Washington, Oregon State University, Rice University, Texas A&M University, California State Polytechnic University, Pomona, University of Kansas, and Iowa State University. The decision framework created in the CoE will ultimately provide decision-makers with a unique set of tools that can be tailored to the needs of specific communities to optimize the design and subsequent management of individual facilities and (inter)dependent infrastructure systems to achieve desired resilience goals while managing life-cycle costs. Its use will provide a basis for targeting public investments and incentives for private investments, thus making it possible to establish a “business case” for achieving community resilience for the first time.

The CoE is developing a multidisciplinary computational environment with fully integrated supporting databases called IN-CORE (Interdependent Networked Community Resilience Modeling Environment) that will enable the factors (and their inter-relationships) that determine community resilience to be fully understood (in this paper, the acronym IN-CORE is used to refer generally to any of its versions). This computational environment will enable a risk-informed decision framework that permits the effectiveness of alternative strategies for enhancing resilience to be measured quantitatively. IN-CORE will be released as an open-source environment to permit user-defined algorithms and databases to seamlessly interface with its advanced risk, loss, and recovery assessment capabilities seamlessly. IN-CORE builds upon previous research that has focused on the response of individual physical infrastructure systems to a single hazard to include multiple hazards and inter-dependent physical systems, which may exhibit significant cascading effects. Nontechnical systems that are essential for the recovery and vitality of a community - financial, social and political support, healthcare delivery, education, public administration - are integrated into the environment, creating a nexus between social and technological infrastructure networks that will narrow the gap between engineering and social science aspects of resilience planning and facilitate risk mitigation and communication among stakeholders. Finally, optimization strategies for enhancing community resilience involving intelligent search algorithms are developed based on identified performance metrics.

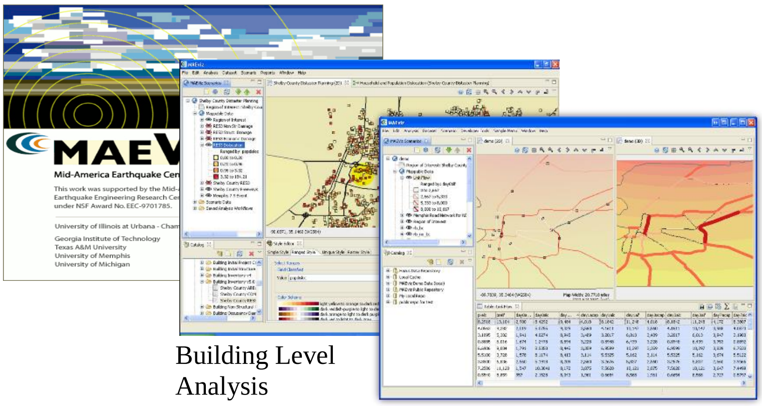
This paper describes the most significant features of IN-CORE. Hazard types include earthquakes, windstorms, tornados, hurricanes, wildfires, tsunamis and floods. Physical infrastructure includes buildings, transportation, water/wastewater, energy, and telecommunication systems, which are modeled with fragility curves (for nodal elements) and repair rates (for linear elements). Social science and economic models support determination of optimal policies to mitigate and recover from hazard events. Interdependencies between physical, social and economic systems, along with the effects of aging and deterioration of the physical infrastructure, are modeled. Community resilience metrics are used to measure the recovery of community functions over time and support decision making and optimization of alternative resilience policies. These features are illustrated with the testbeds and hindcasts that are being used to test, demonstrate and verify the capabilities of IN-CORE.

2. BACKGROUND: MAEVIZ/ERGO

To leverage the work that occurred before the CoE was in established in 2015, IN-CORE's development started from the MAEViz/Ergo software package. The World Bank (2014) conducted a comprehensive review considering over 100 criteria of over 80 open source and open access software packages that quantify risk from natural hazards. The report identified MAEViz/Ergo as "the best software for scenario risk assessment and decision support" and enumerated the advantages of MAEViz/Ergo.

MAEviz/Ergo (http://mae.cee.illinois.edu/software/software_maeviz.html) was developed as part of a joint effort between the Mid-America Earthquake (MAE) Center and the National Center for Supercomputing Applications (NCSA) with initial funding from the National Science Foundation through the MAE Center.

MAEViz/Ergo (Figure 1) is an advanced tool for loss assessment and risk management for buildings, bridges and other infrastructure and network level analysis, primarily for seismic hazards. It was designed to enable policy-makers and decision-makers to develop risk reduction strategies and implement mitigation actions to minimize the impact of natural hazards. MAEViz/Ergo offers several of analyses, ranging from direct seismic impact assessment; to socio-economic implications including 2D and 3D mapped visualizations of the inputs and outputs of analyses; and table, chart, graphs, and reports of the results.



Building Level Analysis

Network Level Analysis

Figure. 1 Snapshots of MAEViz/Ergo

The underlying programming framework that provides extensibility is the open-source Eclipse Rich Client Platform (RCP), which provides a mechanism where developers can add new software modules called plug-ins (Eclipse Foundation, 2013). MAEViz/Ergo is under Mozilla Public License v2.0, and its reliance on an open-source business model, combined with its modular, extensible architecture, addresses many of the issues that limit the utility of other analysis tools.

MAEViz/Ergo provides an extensible spatial analysis environment with a visually-based, menu-driven system. It generates damage estimates from scientific and engineering principles and data; tests multiple mitigation strategies; and estimates impacts of hazards on transportation networks and on social and economic systems. Fragility and repair rate functions are incorporated in for infrastructure systems, including transportation, power facilities, buried pipelines for water and gas, buildings, and bridges. Moreover, capabilities for interdependency modeling also exist, such as interdependency between power network and water network. The socio-economic analyses include estimating expected indoor deaths and injuries, business interruption loss, fiscal impact due to building damage, household/population dislocation, business content and inventory loss. It can compute short term shelter needs, shelter supply needs, and optimize the temporary housing allocation. Figure 2 shows a flowchart of the analyses that can be carried out by MAEViz/Ergo.

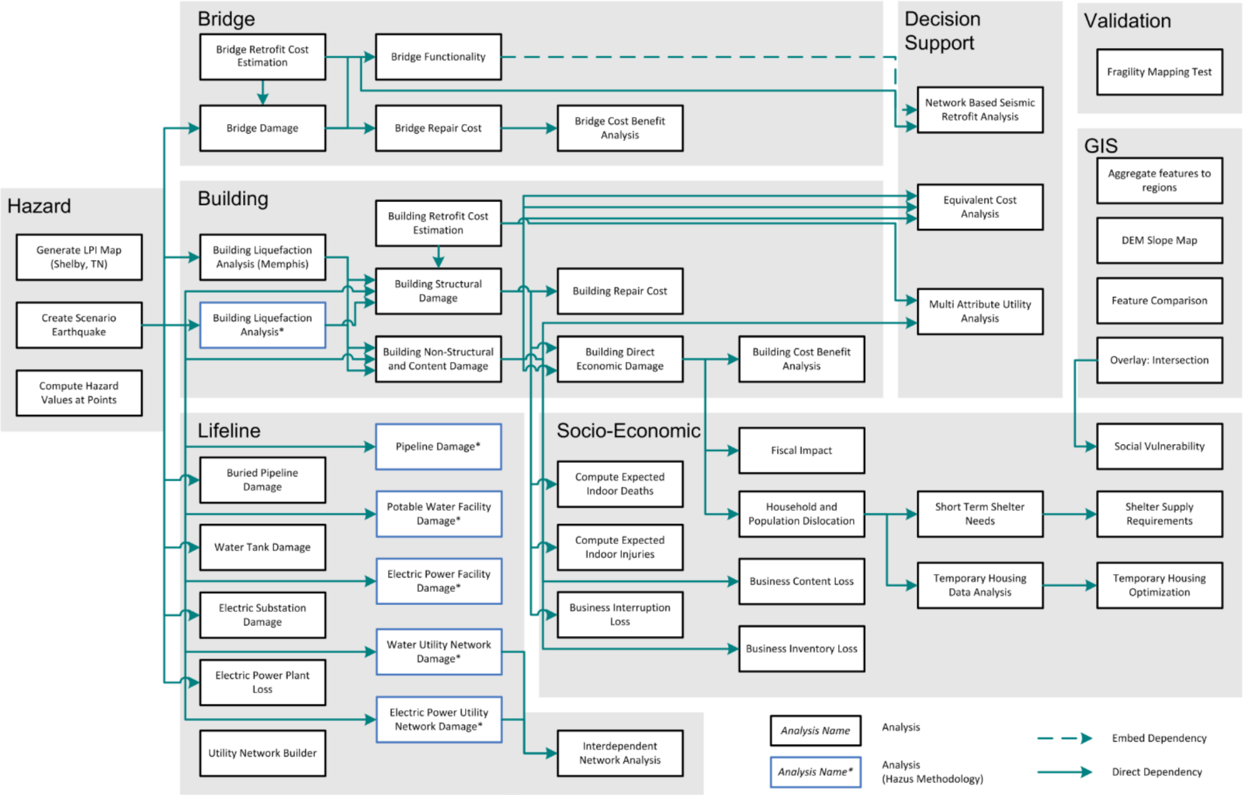


Figure. 2 Flowchart of MAEViz/Ergo capability for earthquake analysis

While MAEviz/Ergo was originally developed for seismic hazards, it was later extended to include inundation due to tsunami. MAEviz/Ergo extends and links engineering models related to building and infrastructure fragilities into broader social (population dislocation) and economic (damage losses and fiscal consequences) consequences. IN-CORE is adding new capabilities to address other hazards and coupled threats, additional system interdependencies and cascading effects, and quantify community impacts at multiple scales for resilience. The next two sections describe in detail the new features and the new architecture of IN-CORE.

3. IN-CORE FEATURES

IN-CORE 1.0 allows the modeling of the impact of earthquakes, tornadoes, tsunamis, and wildland urban interface (WUI) fires as well as infrastructure recovery. Social systems are also considered using state-of-the-research models, and economic impacts are assessed using computable general equilibrium (CGE) models, thus forming a nexus of the engineering, sociology, and economics domains. IN-CORE 2.0 is under development and will include hurricanes, windstorms, coastal storm surge and riverine flooding, as well as multi-hazard and successive hazard events. Next, the paper describes these features in more detail.

3.1 Hazard Scenarios

IN-CORE considers both individual hazards and multiple hazards modeled as scenarios at the community scale to capture the spatial distribution of the demands properly in a community resilience assessment. In general, individual hazard risk formulation is well understood, with the exception of tornadoes and WUI fires, although there is a need for improved characterization of some hazards and their damage potential for application within the computational modeling environment. For hazards modeling in IN-CORE, two levels of models will be available, namely Tiers 1 and 2. Tier 1 hazard models will be executed completely within IN-CORE using libraries and plug-ins developed as part of the CoE research program, and will utilize standard natural hazard analysis technologies. Tier 2 hazard models will provide an option to import data, (e.g., a wind field shape file from an outside source) for the vulnerability assessment of the built environment and socioeconomic impacts. While Tier 2 models will be an option for all hazard scenarios, not all hazard types address Tier 2 options below. The Tier 2 tools will permit more sophisticated modeling when appropriate.

Earthquake: The Tier 1 earthquake scenario requires the analyst to define a fault rupture with a specific magnitude, specified distance and depth, including other attenuation equation-specific parameters. Selection of an attenuation (or Ground Motion Prediction, or GMP) equation from the library available in IN-CORE is required and the option of weighting multiple GMP equations is also available. Utilizing the Tier 2 earthquake scenario will involve, for example, running an external high-resolution, 3-dimensional (3D), physics-based model for seismic wave propagation and importing the ground kinematics into IN-CORE for the assessment of spatially distributed earthquake demands on the distributed infrastructure.

Windstorms: Tier 1 windstorm scenarios include the effect of synoptic (straight-line) winds, such as a Derecho, over a specified spatial region within the community. Synoptic winds are defined as the peak 3-second gust wind speed.

Tornado: Tornado models for Tier 1 analyses will include six types of tornado models. The first four provide the ability to specify wind speeds based on statistics from 45 years of past tornadoes, with either a deterministic or random width and/or length, for Monte Carlo simulations. The fifth is an analyst-defined tornado that specifies the width, lengths, and Enhanced Fujita (EF) regions, and the sixth is a GIS shape file for a past tornado.

Hurricane: Hurricane modeling in IN-CORE will have both Tier 1 and Tier 2 models for the wind field and also for the storm surge and waves. The Tier 1 model is based on the Holland wind field model (Holland et al, 2010) as a function of time. Between 7 and 9 hurricanes from past events will be available as Tier 1 options ranging from a CAT 1 hurricane to a CAT 5 hurricane. The analyst will also specify a track (synthetic or the original) and IN-CORE will determine the peak wind speed with direction spatially across the community of interest by combining the path and historical wind field based on the H*Wind database.

Wave and surge modeling will include both Tier 1 and Tier 2 type models, plus an additional Tier 3 type model. The Tier 1 model will use the USACE's Coastal Hazard System results. These are not available for all locations, but will likely be available eventually. The Tier 2 model will require the analyst to run modeling software outside of IN-CORE and provide the GIS shape file as input to the IN-CORE analysis. Meta-models (or surrogate models) calibrated using the results from the high-resolution simulations will be available in IN-CORE in selected regions. The Tier 3 model will expand the capabilities of the Tier 2 model and will be applicable to other regions without requiring region specific analyses. The Tier 3 model will give a prediction of the storm surge based on data from historical records included in IN-CORE and, if available, external high-resolution simulations. It will also be possible to update the prediction to account for possible site-specific data for a specific region of interest.

WUI Fire: The Tier 1 wildfire modeling is divided into two main components: propagation in wildlands, and propagation inside a community. Currently, the propagation in wildlands is modeled using a Cellular Automata model. The model allows a user to select the ignition location(s) outside of a community and includes the effect of following key features: wind direction and speed, topography, and embers. For fire propagation inside communities, the model uses concept of graph theory to determine the risk of wildfire for any structure inside the community. A probabilistic physics-based model accounts for the following modes of heat transfer: conduction, convection, radiation, and embers.

Tsunami: Tsunami modeling will have Tier 1 and Tier 2 model types. The Tier 1 model follows the recommended procedure established in ASCE-7 (2016) for the 2,500-year return event to establish the spatial distribution of water level in the inundation area. The Tier 2 model consists of running a time dependent numerical model outside of IN-CORE for a specified bathymetry and bare-earth topography with parameterized roughness to account for effects of the built and natural environment. This method will be scenario based but can be used, for example, to develop a Performance-based Tsunami Hazard Analysis (PBTHA) for risk-based analysis.

Flood: The Tier 1 flood model is based on the National Flood Insurance Program (NFIP) maps with the analyst specifying a return period, i.e., 100 or 500 years. Flood depth as a function of location is then identified without consideration of velocity. The Tier 2 flood model will be capable of modeling fluvial (riverine), pluvial (excessive precipitation), and coastal flooding due to sea-level rise. A coupled hydrological/hydraulic illustrative example for the Wolf River Basin in Shelby County, TN (including the effects of climate change) will be available as part of the Memphis Metropolitan Statistical Area (MMSA) testbed using four river basins in MMSA in IN-CORE.

3.2 Physical Infrastructure and Social and Economic Systems

Buildings: Community resilience assessment requires that buildings be modeled at both individual and inventory (portfolio) levels at different resolutions. Because of the diversity of building design and construction practices found in urban communities, it is not possible to provide default fragilities for each building type. An array of fragility models representing different construction practices and recovery approaches will be available for building systems at differing scales depending on the researcher/analyst needs in the context of their analysis.

Transportation: Models will simulate existing roadway and rail networks, with capabilities to evaluate critical routes for response and recovery, identify vulnerable components for upgrade, assess the impact of select retrofits on network performance, and understand the time evolution of key community resilience metrics (e.g., throughput of goods, travel time in the network, access to critical facilities).

Water and Wastewater Network: Models will predict the physical damage and change in functionality of water networks considering water facilities and pipelines, with capabilities to identify critical paths for recovery. The water network analysis uses the Tier 1 or Tier 2 hazard models to develop intensity measures for distributed water network facilities and pipelines. Water service analyses are coupled with physical damage and system repairs over time to give results in terms of water flows and operating pressures, as well as water quality.

Energy Networks: Models for the electrical power network (EPN) and the natural gas network (NGN) will include the ability to analyze the failure probability of electrical power generating plants under researcher-defined scenarios, and include modeling of electrical substations, transmission poles, distribution poles, and generating stations (when relevant, i.e. large cities). The EPN capabilities include a cellular automata algorithm to identify the service area for a given substation based on records of electricity user demand; the EPN algorithms can support any researcher-defined topology through a GIS file upload. An array of fragilities to simulate the expected level of damage and recovery of EPN components are available, as well as algorithms that incorporate work crew limitations.

Telecommunications: Models will simulate wired and wireless networks in the community with an approach similar to the EPN approach. Wired telecommunication systems are assumed to be collocated with electric distribution poles, and recovery of wired networks is dependent on repairs to electric distribution poles. Cellular towers and networks will also be modeled.

Social Systems: Models of social systems focus on population and employee dislocation, housing restoration and recovery, and business interruption and restoration. A suite of tools supports identifying components and concentrations of a community’s population and employees. The tools are based on socio-demographic and socio-economic characteristics that affected by natural hazards and critical for informing post-event demands on infrastructure systems, such as water, EPN, and transportation.

Economic Systems: Spatial dynamic computable general equilibrium (SD-CGE) models are a central component of IN-CORE, with the goal of assisting local, state and national decision makers with both planning and recovery efforts. The SD-CGE models incorporate building and infrastructure damage estimates and population disruptions to provide a range of economic impacts under various building standards, infrastructure capabilities for hazard event types, locations and intensities. These impacts include economic damages, such as production, job, and wage losses in various local economic sectors and their subsequent impacts on local residents, including health, income and migration.

3.3 Interdependency and Damage Modeling

Interdependency: IN-CORE models interdependencies within and between physical infrastructure systems, and social and economic systems. Interdependencies can change over time, depending on the level of initial damage and the recovery process. Examples of interdependent modeling for physical infrastructure systems are illustrated with respect to the water network. The water network capability analysis allows the user to include the dependency of the pumping stations on supporting EPN sub-stations. This dependency affects both the initial damage scenario, with a damaged pumping station or EPN substation, and the recovery process, where the recovery of the pumping station may be dependent on the recovery of the EPN substation.

This modeling capability is being extended to the interdependencies between social and economic systems and physical infrastructure. Returning to the water network example, models of household dislocation and water network recovery will be integrated. The analysis can simulate the effects of population dislocation due to buildings damage leading to (reduced) water network demand following a damaging event. The analysis can also simulate the effect of water network disruption leading to population dislocation and decisions to relocate during the recovery process. The EPN and water networks can be linked with household dislocation and recovery, employee dislocation, business interruption, and economic impacts. Healthcare services, schools, and employee availability depend on the performance of the transportation system (primarily roadways, bridges, and railroads) within the community.

Aging and Deterioration: The effects of aging and deterioration on infrastructure components and define time-variant fragilities and repair rates for the damage analysis of networks will be incorporated in IN-CORE. The users will have the option to specify the input parameters that are needed in the relevant aging and deterioration models (e.g., age, environmental conditions, loading/hazard conditions, spatial variability for large infrastructure network).

3.4 Recovery Modeling

IN-CORE will include recovery models with the ability to conduct spatial and temporal updates as field data becomes available. More specifically the following functionalities will be included:

- Buildings: Recovery of functionality for intended use;
- Transportation routes: Recovery of routes to critical facilities and critical infrastructure components;
- Water/wastewater: Recovery of services to buildings and infrastructure systems;
- EPN: Recovery of services to buildings and infrastructure systems;
- Telecommunication: Recovery of services to buildings and infrastructure systems;
- Social Systems: Recovery of services; and
- Economic Systems: Recovery of services.

3.5 Performance Goals and Resilience Metrics – Community and System Levels

The recovery will be measures using community and system level resilience metrics defined by the CoE. Performance goals are aspirational, such as maintaining population stability after a hazard event and during recovery. Metrics directly or indirectly measure to what degree a performance goal has been met. Example community performance goals and metrics include (performance goal: metric):

- Population stability: Changes in dislocation, jobs, and housing;

- Economic stability: Changes in taxes and revenue (resources), and budget (needs);
- Social Services stability: Functionality of governance, healthcare, education, retail, and banking; and
- Physical Services stability: Functionality of buildings, transportation, water, wastewater, electric power, gas, and telecommunication.

3.6 Decision and Optimization

The characteristics of the physical infrastructure and social and economic systems that can be used to modify the hazard impact can be identified and used as levers in an optimization process targeted at 1) reducing the vulnerability of a community by prior planning and 2) accelerating the community's recovery following a hazard event.

4. IN-CORE ARCHITECTURE

This section presents the architecture of IN-CORE 1.0 and IN-CORE 2.0.

4.1 IN-CORE 1.0

IN-CORE 1.0 is an open source Java application with a plug-in based architecture called the Eclipse Rich Client Platform (RCP). This type of architecture allows researchers to extend IN-CORE's capabilities through the addition of new science/features by adding new plug-ins. These features can be connected with the existing 40+ analyses in MAEViz/Ergo to produce new results.

The core technologies of the MAEViz/Ergo platform include Eclipse RCP, Geotools, Visualization Toolkit, JFreeChart, KTable and Jasper reports. Note that those technologies are all open-source projects. These technologies make up the core of MAEViz/Ergo and provide capabilities such as; data management, visualization, analysis, etc. These components and their hierarchies are illustrated in Figure 3.

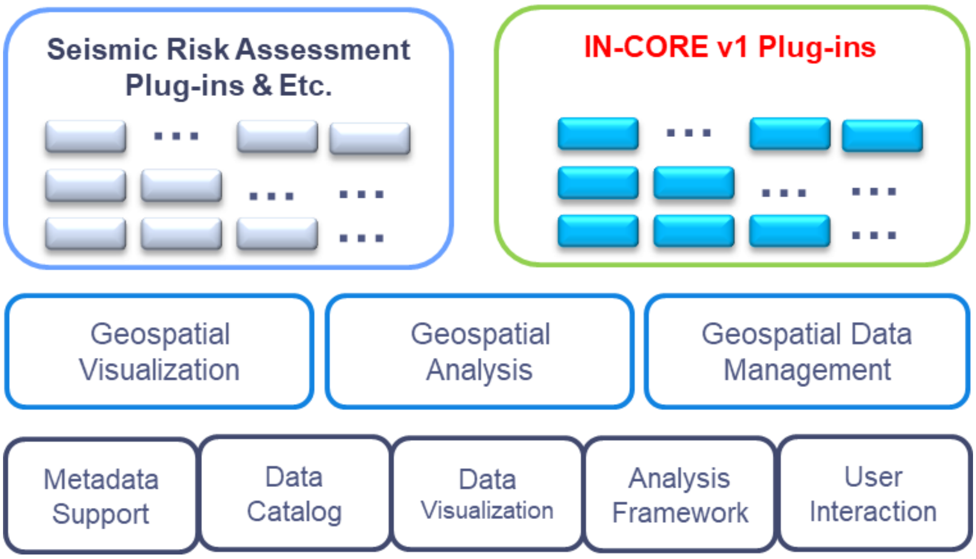


Figure 3. IN-CORE Version 1 Architecture

4.2 IN-CORE 2.0

IN-CORE 2.0 is currently under development. It will be a web-based application that includes the capabilities of IN-CORE 1.0 while adding extensive new capabilities. Some of these new capabilities include a REST API, support for additional languages such as Python, support for spatio-temporal data, multi-variate fragilities, communicating with external tools such as OpenSEES, overlaying data from web sources such as OpenStreetMap, NBI, NOAA, etc.

There are two architectural design patterns adopted for IN-CORE 2.0: 1) Service-oriented architecture (SOA), and service API (Application Programming Interface) gateway. The SOA is a style of software design for creating web services for units of functionality identified for the application system. In our implementation, the web service is RESTful (Representational State Transfer) web services. The SOA brings flexibility of developing thin/light-weight clients such as a web application. Furthermore, it allows users to access each service directly from their own scientific application. The service API gateway provides a single-entry point so all web services are accessible via a gateway software (or service). Thus, the API gateway handles authentication, authorization, traffic control, etc. for all services and it allows the implementation of each service to be loosely coupled and light-weight.

Figure shows these two architectural design patterns. Users can access the service via a web application (similar functionality as IN-CORE 1.0) or a client library in Python. By using the Python library, users can utilize the services they need in their algorithms. In addition, it allows researchers to use the same implementations/data, reducing redundant development. The currently planned services are defined as shown in Figure 4:

- Data semantic service: managing/querying metadata of analysis, data, vocabulary, definition of data types, etc.;
- Data service: managing/querying/storing data;
- Hazard service: computing various hazard intensities for different hazards (e.g., ground shaking in peak ground acceleration (PGA) for Earthquake, wind speed in miles per hour for tornado);
- Fragility service: managing/querying/storing various fragility curves, restoration curves, etc.;
- Analysis service: Managing/computing analysis;
- Maestro service: managing analysis definitions and related information for users working with the analysis service; and
- Geospatial visualization service: providing/generating geospatial visualization (e.g., 2D map).

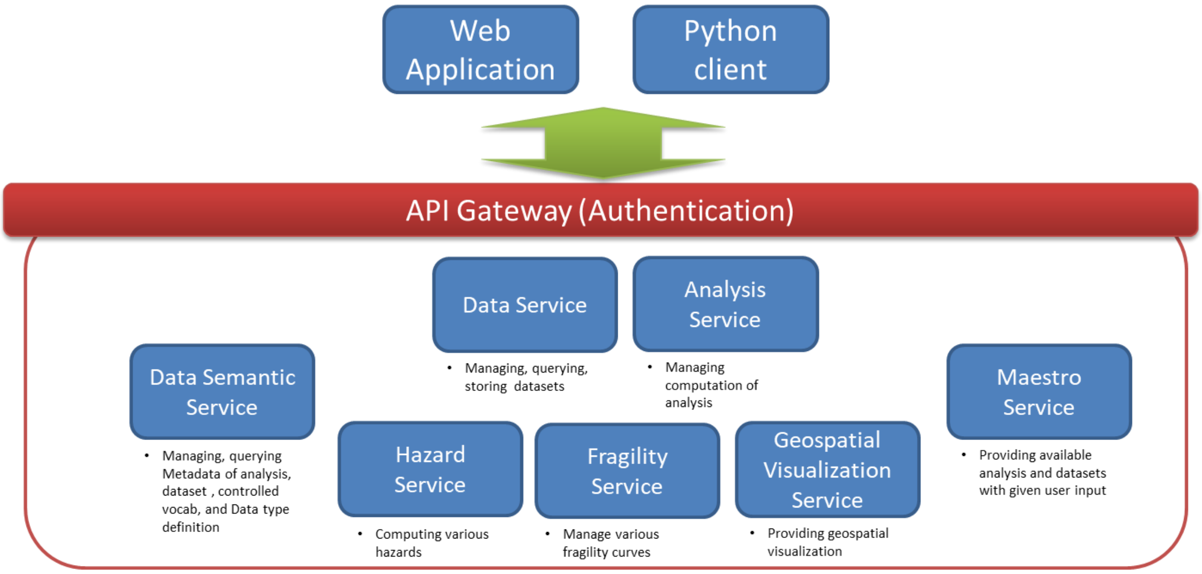


Figure 4. IN-CORE Version 2 architecture

5. TESTBEDS AND HINDCASTS

During the development of IN-CORE, four testbeds were developed to allow researchers to test and explore their developed algorithms related to community resilience. These four testbeds will be included in IN-CORE for researchers to learn, expand upon, and validate their own algorithms as they expand IN-CORE. The Centerville Virtual Community is an idealized community of 50,000 people with a reasonably diverse and representative economy, physical systems, and demographics, and will provide researchers a simplified illustration of how individual infrastructure portfolios and infrastructure systems and their dependencies can be modeled, and how linkages between performance of buildings, transportation, energy and water systems, economic and social systems can be established for community resilience assessment purposes. An initial decision framework was developed within the original version of Centerville and tested successfully for two simple problems involving optimizing pre-earthquake retrofit strategies in Centerville. Documentation for Centerville was published in a Special Issue in *Sustainable and Resilient Infrastructure* (published by Taylor & Francis as Vol. 1, Issue 3-4, December, 2016). In addition, the Centerville testbed formed the basis for the development of a typical community building portfolio consisting of 19 building archetypes, which is being used in other testbeds and hindcasts within the CoE.

6. CLOSURE

The National Institute of Standards and Technology (NIST) funded the multi-university five-year Center of Excellence for Risk-Based Community Resilience Planning (CoE), headquartered at Colorado State University, to develop the measurement science to support community resilience assessment. The measurement science is implemented in a computational environment with fully integrated supporting databases to model the impact of natural hazards to communities as well as their recovery, evaluate the key attributes that make communities resilient, and optimize resilience enhancement/planning strategies.

The key features and architecture of the Interdependent Networked Community Resilience Modeling Environment (abbreviated as IN-CORE) includes the impact on aging and deteriorating (inter)dependent infrastructure of earthquakes, tornadoes, tsunamis, and wildland urban interface (WUI) fires, hurricanes, coastal storm surge, as well as the recovery of functionality for buildings and infrastructure and supported social and economic systems. Social systems include dislocation, housing recovery, business interruption. Economic impacts are assessed using computable generalized equilibrium (CGE) models. Thus, IN-CORE forms a nexus of the engineering, sociology, and economics domains.

7. ACKNOWLEDGMENTS

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