# Human Systems-of-Systems, a Methodology and Measurement Framework for Community Resilience

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*Abstract*— **Community resilience, which focuses in on combined social and technical measures of resilience, continues to receive a great deal of attention in literature. A large number of frameworks have been developed that attempt to combine physical measures of place with measures reflecting social interaction as the basis for predictive measurement of the resilience of a community, including one from the authors. These frameworks form the basis for development of human analytics, particularly to help understand community resilience in the mitigation and preparation phases prior to disruptive events. However, very few examples of actual measurement programs are in place, and even fewer that use dynamic measures of human and social resilience. This paper builds on a methodology for characterizing human communities as Systems-of-Systems (SoS), and proposes the development of active community resilience analytics that track the continuing resilience of a community. This is a multi-scale problem, and the SoS framework is critical to development of a measurement architecture that reflects both long-term and short-term human resilience measures.**

***Keywords-community resilience; resilience measurement; human analytics; systems-of-systems; sociotechnical systems.***

## I. INTRODUCTION

This work investigates human social analytics from a Systems-of-Systems (SoS) viewpoint using the context of community resilience. A SoS is a set of systems that interact together to produce outcomes no single system can accomplish on their own. Examples are electrical grids, rail networks, networked sensors, etc. In the resilience context, the combined community social systems, the built environment, and infrastructure systems create a large complex SoS.

Key defining features of SoS are the independence of each constituent system and the emergence of new outcomes that are unique to the whole of the SoS and not present in any individual constituent system. SoS Engineering is a discipline and methodology that seeks to define and optimize networks of interacting systems (old and new) toward common purpose and requirements [1].

This paper discusses methods and tools for "Human SoS," which addresses the interaction between networks of human and engineered systems. Understanding and classifying both the social and technical aspects of large complex systems forms the starting point for analyses of any SoS behavior. The focus on Human SoS suggests a human-centered or participatory approach to understanding and designing SoS evolutions. Human SoS methods combine aspects of Complex Systems Engineering (CSE), SoS Engineering (SoSE), and traditional Systems Engineering (SE). These present series of methods to structure and manage a set of interacting constituent systems toward a specific set of goals or purposes [2][3]. Modeling the specifically human interactions is a key to successful SoS development, but is often ignored or oversimplified in SoS design, which is why an explicit focus on Human SoS is useful.

The interaction between human community development and city infrastructure renewal in urban communities is an example context. An urban community is a shared human and engineered architecture comprised of a complex set of constituent systems. One would hope the human systems and engineered systems that support the human communities would be designed toward common outcomes and measures. In practice this seldom occurs, particularly with urban infrastructure. While the need for efficiency and scale drive city infrastructure development, the inherent vulnerability, resilience, and sustainability of human communities allows the city to withstand and recover from shocks. The disciplines of engineering and the social sciences rarely come together to address these equally, except on occasion to address natural disasters. Shocks to urban communities can be disaster events, but also equally damaging economic, communication, and demographic changes.

Metrics and models do exist to evaluate resilience of both infrastructure and human well-being, but very few research efforts consider their dynamic performance and function working together. This is an area where human social analytics are sorely needed. In this context, SoS principles are most useful to structure representative analytical measures. This paper will not present a survey of community resilience frameworks, as multiple other authors have done that. This paper will use the community resilience framework previously reported by the author and past co-authors [4]-[7] to discuss the SoS principles and associated human social analytics of community resilience.

Section II of the paper introduces the Human SoS concept. Section III briefly discusses the community resilience framework. Section IV uses the Human SoS concept and the community resilience problem to briefly discuss model development. Section V provides an example of the analytics needed.

## II. THE SYSTEMS OF SYSTEMS VIEW

Social Systems are the patterns formed by the interrelationships between individuals, groups, and institutions that together form a whole. Sociotechnical Systems are technology-driven systems that involve significant human and social participation, and that participation in turn influences the architecture and design of the technical system. In such systems both the human/social participation and the engineered system co-adapt over time [8]. Human SoS relates to the intentional design of the social systems in conjunction with the design of a larger sociotechnical SoS. Examples are infrastructures, organizations, political systems, and large product/service platforms.

Human SoS demonstrate several consistent patterns that have been studied by a number of authors. These can be generalized into an analysis process to accelerate the stakeholder's and system designer's learning in the domain of Human SoS architecture. The process highlights the SoS characteristics of a complex system architecture and causes the architect to directly experience them in participatory sessions with stakeholders. Table 1 lists the process.

TABLE 1. ARCHITECTURAL ANALYSIS OF A HUMAN SOS.

| | |
|---|---|
| SoS Perspectives | The tension between perceptions and facts often form the best starting place to understand the behaviors in a Human SoS. Understanding perspectives is a stakeholder research process best informed by talking to stakeholders. |
| SoS Definition | A process to identify context, SoS boundaries, appropriate scales and constructs, and enablers or barriers that might exist in the context of interest. |
| Multi-layer Abstractions | Identifying all of the actors at each societal layer and "what they bring with them" - what abstractions would represent primary performance measures of the current SoS and the desired evolution. |
| SoS Outcomes | Modeling dimensions of the SoS considering system outputs, outcomes (or goals), and the interactions that cause them. |
| SoS Communication | Identifying information flows that are relevant to decision making in the SoS. This should include transparency (availability to all parts of the system), timeliness (to make decisions), accuracy, and trust. |
| SoS Implementation | Human SoS have no single mechanisms of control. Behaviors arise from leadership and incentives instead of authority and control. The architect must design interventions that influence change in the SoS. |

The process has proven to be particularly useful in understanding and designing the human characteristics of SoS, which we call Human SoS. This is a structured method that walks the participants through selected stakeholder perspectives, helping to define the SoS, building representative abstractions at different layers of the SoS, agreeing on outcomes, understanding flows, and finally designing alternative implementations of the SoS. A defining analysis process in Human SoS is the determination of multi-layer abstractions. Human communities and enterprises are organized into layers, such as individual/group/society structures or enterprise people/process/organizational structures. This is important when designing a Human SoS – success measures often differ at different layers and the relationships between different constructs or abstractions is often a complex model.

## III. HUMAN SOS: URBAN COMMUNITY RESILIENCE

Figure 1 represents a conceptual model of human community resilience represented at multiple scales – the lowest being a human capital construct that describes the human components of standard of living (SoL) and subjective well-being (SWB) critical to community populations. The human capital model was derived in the context of urban communities and their built environment and further in the domain of a city with its infrastructure and environment. Previous research developed a complex structured equation model that relates over 130 human capital development measures to measures of critical infrastructure redevelopment [6]. This model is a representative framework to describe most large urban settings in the United States, other contexts would need adjustments to the model.

Human communities and city infrastructure are strongly coupled interdependent SoS, and they cannot successfully be designed using simple indices or optimization of individual components. There is a need to model these systems using complex representations of human and community development, participatory methods that address system complexity to engage communities and planners, and next generation social analytics tools to evaluate predicted, short-term, and long-term effects of resilience building.

A recent National Institute of Standards and Technology report from a workshop on community resilience evaluated seventeen different approaches to measuring community resilience. They found that none of the frameworks could answer two basic questions: "1. How can community leaders know how resilient their community is?" and "2. How can they know if their decisions and investments to improve resilience are making a significant difference?" They also found that a single set of prescriptive measures or indices was unlikely to support neither all types of communities nor all contexts for planning. The subsequent goals were to develop "community resilience metrics or tools that will reliably predict the physical, economic, and social implications (either positive or negative) of community decisions (either active or passive) made with respect to planning, siting, design, construction, operation, protection, maintenance, repair, and restoration of the built environment." [9]

Community leaders need new decisional analysis methods and tools that directly address these two basic questions. These methods and tools must blend the disciplines of participatory design and development with psychology, engineering, and computer science. In order to effectively model community resilience, one must be able to generalize approaches to the context of local community-specific factors. The definition of appropriate context is a stakeholder agreement process. Current state of community development practice recommends reduction into a few simple to understand (by stakeholders) measures. As a result, the

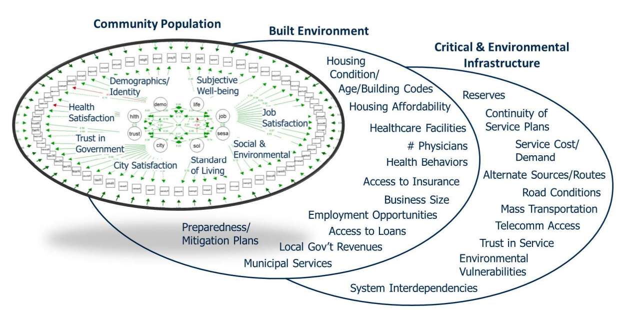


Figure 1. Complex Model of Resilience to Account for Human Capital.

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complexity of the environment is lost and the effectiveness of the intervention becomes a debate. In today's era of big data analytics and social network analysis, much richer measures and deeper understanding of results are possible.

Models and measures are needed for optimization of the Human SoS in scenarios and dynamic models that represent both development and collapse of community infrastructure and social constructs (Figure 2). In development scenarios, planners use infrastructure renewal projects and community development to reduce inherent vulnerabilities and build inherent resilience capacity. In disruptive times, crisis response is a reaction to events, development of coping responses is a reinforcement against collapse, and inherent resilience (or sustainability) could be viewed as an attempt to prevent future collapse. The relationship between human capital and shocks are most often represented as a set of capitals that support the coping response of the community [10]-[12]. Example disruptive scenarios are not just natural disasters, they include community gentrification, economic shocks, infrastructure or information collapse, and disaster events. Measures of inherent resilience must address all cases.

## IV. Human SoS and Human Analytics Model

Models of the Human SoS and associated analytics support development of decision analysis tools and a multidisciplinary view of community resilience, focused on factors that are known to affect resilience of human populations in areas that are highly dependent on shared infrastructure. Such a toolset would provide a means to integrate often-competing views of infrastructure and community development programs into common outcome measures focused on human community development.

A Human SoS model of resilience must include the social dimensions and the built environment/infrastructure of a community, the constructs that link these together and to long-term community goals, and the plan for both resilience development activities and disaster response. In the SoS context, achievement of resilience is often how well the constituent systems either interact together or fail to do so. Effective gap analysis and understanding of the short and long-term interactions between community and infrastructure development goals, is critical to this process. Measures and models that effectively capture community learning and likely resilience building outcomes are needed. There is a further need for locally scaled data to be used consistently and appropriately in conjunction with nationally scaled measures supporting national preparedness goals. This is a challenge: finding a consistent set of measurement indicators that are usable by community leaders, but also are valid at local to national scales. Predictive models of community resilience require a much richer selection of qualitative indices and also integration of dynamic models that reflect flows of resources and flows of information.

The conceptualization of a Human SoS modeling and decision support platform would address all of the domains of Figure 3 - conceptual models that reflect model-based analysis of the enterprises under study; data models and datasets that capture both current and future trends; complex system models and simulations to create predictive analyses; and custom visual analytics that allow researchers and policy makers to interact with the data and simulation. The point of Figure 3 is that simple selection and presentation of data does not represent the definition of a Human SoS and an appropriate level of complexity. Human SoS are enterprises and the data must be represented in an appropriate enterprise model that reflect the relationships between data sets and their interdependencies. A second point of Figure 3 is that the collection and curation of data is becoming more prevalent in human settings and the relationship between the enterprise model and the data must be explicit and explanatory. A third point of Figure 3 is that predictive analysis of the data must be incorporated into the appropriate type of computational complex system model based on the purpose of the analysis. This model must use the curated data appropriately. The final point of the Figure is that the communication of the data and the analysis must be in an appropriate visualization form so that the human reviewer can discern the intended patterns. The Human SoS framework helps to consider all of these factors.

We envision the development of such a platform in a community resilience setting as a multidisciplinary activity

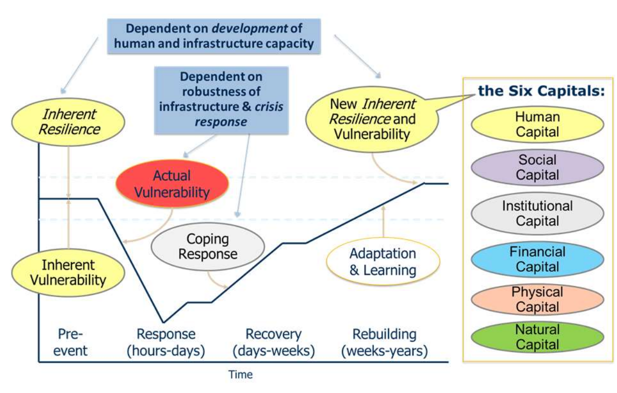


Figure 2: The Dynamic Process of Community Resilience.

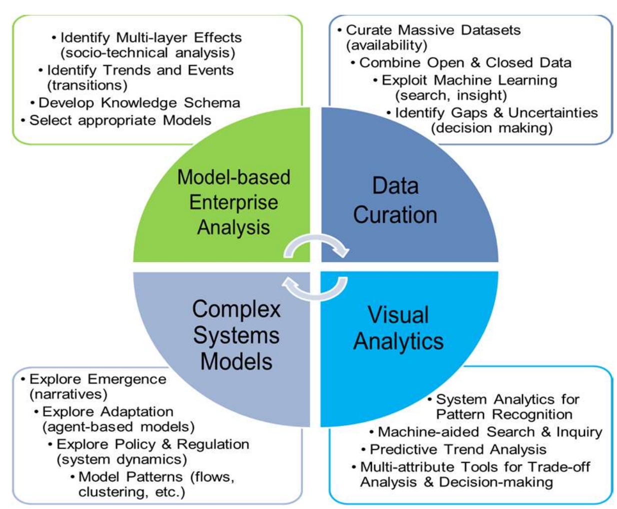


Figure 3: Convergence of Facilitation, Modeling, & Data Analytics Using Modern Software Tools and Methods.

that brings together: 1) Participatory Model Development to engage community stakeholders using a Human SoS architecting methodology, 2) a Complex Model of Human Capital integrated as a decision analysis tool, and 3) a Dynamic Modeling Framework simulating resilience scenarios for predictive analysis and validation using community measured data.

The participatory model development engages with local communities and planners to in a participatory setting using the Human SoS analysis framework of Table 1. The SoS Engineering process would proceed as follows: 1) *SoS Perspectives* involves stakeholder interviews and a conceptual modeling process to identify stakeholders and incentives, the critical interactions in the system that could be used as levers for change, and the measures at different abstraction levels that inform the computational models. 2) The *SoS Definition* is the communities and infrastructure of a city. Models, data, and evaluation research would be bounded to focus specific neighborhoods in the city based on their differing physical characteristics, demographics and social characteristics, and planned development goals and timelines. 3) *Multi-Layer Abstractions* are collected as a set of measurements at representative local and broader scales. 4) *SoS Outcomes* are the respective purpose, goals, and strategies of the systems as envisioned by the stakeholders. These represent intents when embarking on programs to change the systems. 5) *SoS Communication* models the relationships and flows across the defined city resilience model. In this model, the dynamic process of resilience is placed into a model that could capture the representative process relationships and identify measurement points. 6) *SoS Implementation* is a representative model of the technical, economic, and social factors representing the SoS.

These factors come together in a set of complex decision models. It is unlikely that a single model will be able to represent the full complexity of an urban community, but capturing the correct set of dependencies as an SoS model will help to identify emergence (intended or unintended) that arises from combinations of change programs. Over time, this work envisions a tool that policy makers can use that will quickly reveal how changes in funding or resources may impact community resiliency. Such a tool would have an easy-to-use graphical user interface allowing policy holders - regardless of their statistical or programming backgrounds - to understand trends in human capital and community resiliency in an effort to better predict how changes in community resources will impact communities as a whole. Such a tool should include an explorable model of the Human SoS constructs so users can see for themselves the underlying structure of community resiliency. It should also generate trending measures and maps revealing community resiliency at a local and national level. The tool should provide users with valuable information about the statistical and analytical procedures used to create the models in an effort to make the models as transparent and easily communicable as possible. Ideally, policy makers will be able to use this tool in order to make more informed decisions about how to allocate funding or improve communities in a resiliency context.

## V. Human Social Analytics Example

Hollnagel describes resilience in systems as being able to respond appropriately to both disturbances and opportunities. He further defines resilience not just as properties of a system, but as its resulting performance [13]. Programs that attempt renewal of infrastructure or community assets should address these as opportunities to increase the resilience of the community as defined by the activities and services provided by and to the human occupants of the community. Figure 4 shows the complex relationships between the objects and processes that define a city. One might consider the input to be the city infrastructure networks that provide services supporting the livelihood of the communities, and the output to be the development of human capital that provides for sustainable and resilient livelihoods of the cities occupants.

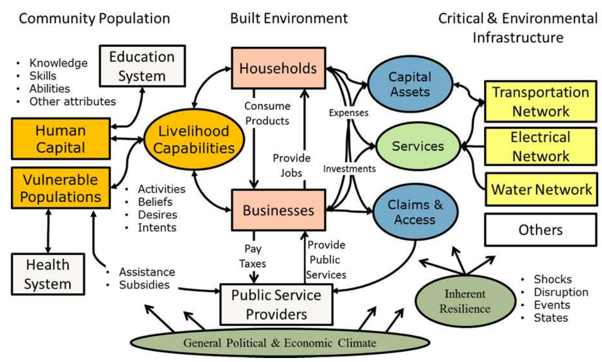


Figure 4: Architecture of a City Representing the Relationships Between Infrastructure, Built Environment, and Community Populations.

A complex model might consider the regentrification of a set of neighborhoods via investment in new city infrastructure and built environment. This development would include support to vulnerable populations with improvements to assisted living for the aging and disabled as well as improved overall community access to healthcare. Tables 2 and 3 list several factors associated with infrastructure, built environment, and human capital that should be considered when addressing community healthcare. Table 2 lists the viewpoints of the city planners, while Table 3 identifies the related human capital components.

TABLE 2. URBAN SOS MODEL OF HEALTH AND ACCESS TO HEALTHCARE.

| Model Component | Factor |
|---|---|
| Housing for Vulnerable Groups | Public shelter capacity |
| | Age of structures (year built/building codes) |
| | Housing burden (housing cost/income) |
| Energy Services | Availabilty (average down times) |
| | Energy burden (total cost of energy/income) |
| Health Management | Medical facilities and practitioners |
| Accessibility | Access to transportation |
| | Access to communications |
| Land Use | Parks and recreational facilities |

TABLE 3. HUMAN SOS MODEL OF HEALTH AND ACCESS TO HEALTHCARE.

| Model Component | Factor |
|---|---|
| Standard of Living | Physical health condition |
| | Need for public transit vs. access |
| | Income |
| Subjective Wellbeing | Subjective satisfaction with physical health |
| | Subjective satisfaction with city |
| Security Climate | Afraid to walk in neighborhood at night |
| Political Climate | Opinion of gov't spending on healthcare |
| | Opinion of gov't spending on mass transit |
| Demographics | Size of city |

In the human social analytics domain, monitoring of individuals health condition, as well as their access to healthcare and medical facilities is possible. Poor health is a social vulnerability that will impact the resilience of the human community to shocks. The model above identifies a number of areas of monitoring: access to housing and energy, actual health condition, satisfaction with health, ability to get to medical treatment facilities, and assessment of the city in terms of ability to gain exercise.

Measurements of the built environment and infrastructure are long-term and medium term indicators that would be reflected in a city planning dataset that is maintained year-to-year and adjusted based on the age of the neighborhoods and changing land use patterns. Medium term measures like housing and energy burdens reflect economic conditions that should be tracked regularly and fed into planning activities. The primary challenges with these measures are collection and maintenance of the data at city scales.

Likewise, satisfaction with health and city as well as political climate are factors that should be surveyed and monitored in the medium to long-term at individual and community scales. For the other factors, the availability of social media data, wearables, mobile location data, and other community sensors provide opportunity for near real-time analysis of community patterns. These would include individual monitoring of health vulnerabilities, patterns of mobility, and routine use of wellness opportunities such as parks and recreation. Neighborhoods with lower health indices can be targeted for improvement as well as monitored in response situations.

Putting together a monitoring system that tracks near real-time resilience indices for communities that have varying human capital concerns is possible given priorities and a well-constructed human SoS architecture. It is critical that such a model be defined so that the effectiveness and long-term validation of health capital development programs can be tracked. The complexity of this model should also not be underestimated, but the future of human social analytics needs to be placed in a framework that adequately reflects the complexity of these Human SoS. This paper discusses a framework for development of these models.

## VI. CONCLUSIONS

The exploration of the human characteristics of SoS over time led to the development of a framework for SoS analysis that captures purely human outcomes. We call this Human SoS. Key to the analysis is a set of six processes that encourage systems thinking and model development with respect to the human communities that use these systems. These are SoS Perspectives, SoS Definition, Multi-layer Abstractions, SoS Outcomes, SoS Communication, and SoS Implementation. We have evaluated and tested these processes in a number of studies, primarily focused on community resilience, but also in other contexts such as organizational skill retention and political corruption.

The complexity and social adaptation represented in collaborative SoS make the decision space nearly impossible to navigate without a combination of participatory stakeholder driven analysis tools and extensive modeling and simulation. The hope is that the engineering communities, social science communities, and design communities will eventually come together to find common model-based conceptual design approaches that bridge current gaps across disciplines. At this point the community should focus on methods to sense and capture the human analytics that continuously evaluate these metrics.

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