Linking community capital measurements to building damage estimation for community resilience

By

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ABSTRACT

Community-level resilience has become an important consideration for city planners, policymakers, and other decision-makers, and therefore, it is increasingly investigated by engineering researchers. The robustness of the built environment and interconnectedness of the social system are important factors affecting community-level resilience that need further investigation. Recent research and studies show a need for the buildings to stay operational to preserve the quality of life after a disruptive event [Sattar et al. (2018)]. Disasters cause significant disruption to social institutions, the local economy, and overall quality of life due to damage to buildings and other civil infrastructures. Understanding the relationship amongst different community functions mainly between buildings and organizations, is a significant part of the motivation behind this research.

There are seven types of capital inherent in a community: financial, political, social, human, cultural, natural, and built [Flora et al. (2008)]. This work advances the current state of knowledge in the relationship between buildings (a subset of built capital) and organizations throughout a community through a novel quantitative framework based on the seven community capitals. This thesis proposes a two-tiered approach, where one tier is performed at a community-level, and other tier is performed at a building-level and then integrated to measure post-disaster community capital losses. The community-level losses were measured using a novel scoring system based on keywords defining each community capital capturing changes in each community capital induced by building damage. The second tier measures building-level losses including number of damaged buildings as a proxy for built capital, dislocation rates for social capital, morbidity rates for human capital, accessibility changes for political capital, and repair costs for financial capital.

The framework is exemplified on a virtual community, Centerville, under an earthquake scenario. Centerville is comprised of multiple building types with varying robustness [Ellingwood et al. (2016)]. Occupancies that are used to assemble the building inventory of Centerville include residential, commercial and industrial, as well as critical facilities such as hospitals, fire stations, schools, and government offices modeled using 16 building archetypes. The community is also comprised of a synthetic population with varied attributes linked to social vulnerability and resilience. The framework presented is hazard-generic, however for demonstration the hazard considered for this thesis is seismic and is adapted from Lin and Wang (2016). Disaster impact measurements are examined across the building portfolio for the earthquake scenario at different points in time to support comparisons. Although earthquake demand and some measures of community capital remain ill-defined, the proposed framework demonstrates the relative importance of including community capitals in loss estimation models to calculate community-level performance and resilience objectives.

Resulting community capital measures, which aid community decision makers in either mitigation plans or as part of post-disaster response and recovery efforts post-disaster, are provided using a community capital ‘dashboard’. A dashboard presents trade-offs for supporting decision makers in understanding how changes to characteristics of the community can enhance or inhibit community resilience. Additionally, a dashboard enables the user to see the trade-offs across multiple criteria that influence community resilience, as opposed to a single measure that may be too vague for a decision maker to understand. The purpose of this work is to aid community decision makers in either mitigation plans or to aid in response and recovery efforts post-disaster through a holistic view of disaster impacts on their community.

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Chapter 1: Introduction

1.1 Motivation and objectives

With a growing number of disasters, subsequent losses and disruptions, community resilience needs essential research and implementation. The NCEI (National Centers for Environmental Information), a subset of the National Oceanic and Atmospheric Administration (NOAA), collects data for severe weather and climate events in the U.S and globally to address its economic and social impacts. On that account, NCEI's data from 1980 to 2018 [NCEI, (2019)] is used as a reference to convey the reality of the rising number of disasters and losses and as a result the exigency for community resilience. Figures 1-1 and 1-2 illustrate the rise in the number and cost of disasters due to the combined effects of increased exposure, vulnerability, and climate change. In the U.S. in 2018, 14 billion-dollar disasters caused the 4th highest total number of events and fourth-most costliest year for weather and climate disaster losses, following 2017 with 16 events (the most expensive year on record) and 2016 with 15 billion-dollar events. Hurricane Harvey (2017) had a major impact on the socio-economy of Texas causing $125 billion in damage [NHC, (2018)] and 89 deaths [Afiune, (2017)]. The aftermath was that the damage to residential buildings left many families homeless, and government officials recognized the recovery process will take years. On this ground, measuring and improving community resilience should be a top priority for city planners, engineers and researchers now more than ever as it aids in the understanding and reduction of society's vulnerability to disasters.

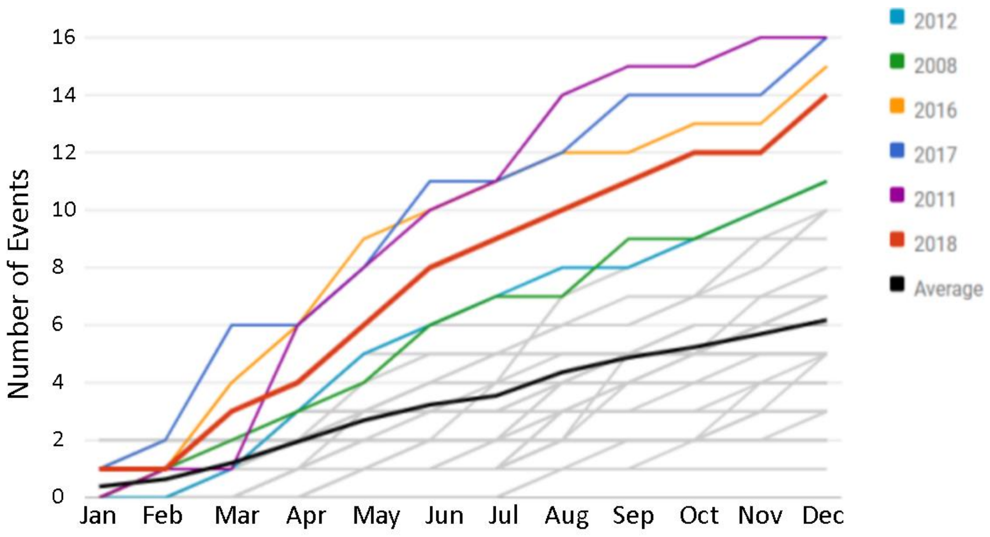

Figure 1-1. 1980-2018 Year-to-Date United States billion-dollar disaster event frequency, NCEI, (2019)

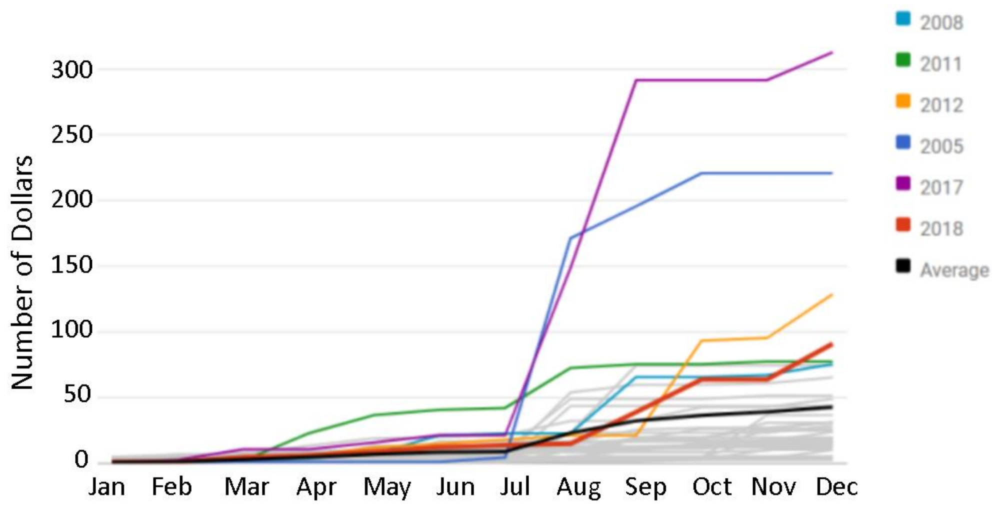

Figure 1-2. 1980-2018 Year-to-Date United States billion-dollar disaster event cost, NCEI, (2019)

During disasters, a portion or all of the components of a community are affected. Here, these components are articulated as seven community capitals: financial, political, social, human, cultural, natural, and built capitals. This thesis uses the definitions of these seven community capitals utilized in NIST (2016) and adopted from Ritchie and Gill, (2011) as:

1. Financial capital – Available financial savings, income, investments, and credit at the community-level that is instantly accessible.
2. Political capital - The ability to engage external entities in efforts to achieve goals and the ability/power to access and influence the distribution of resources.

3. Social capital - Social networks, associations, and the trust they generate among groups and individuals within the community
4. Human capital - Knowledge, skills, health, and physical ability of community members
5. Cultural capital - Language, symbols, mannerisms, attitudes, competencies, and orientations of local community members/groups
6. Natural capital - Resources, such as air, land, water, minerals, oil, and the overall stability of ecosystems
7. Built capital - Buildings and infrastructure systems within a community

Post-disaster studies demonstrate a need for buildings, as well as other physical infrastructure, to stay operational in an effort to preserve community functioning after a disruptive event [Sattar et al. (2018), Koliou et al. (2017), NIST (2016), McAllister, (2015)]. The widespread and disproportionate impact disasters have on communities provides the impetus and motivation behind this thesis. The goal of this thesis is to generate new knowledge connected to the intersection of the seven capitals with community disaster resilience through a novel framework demonstrated through a seismic scenario analysis. The principal research question addressed here is how can the seven community capitals be measured and used to improve community disaster resilience? This research question is examined through the following research objectives:

1. Associate post-disaster impacts with the community capitals and incorporate into a loss estimation framework.
2. Develop relationships between building occupancy and organization type with the community capitals and incorporate into the loss estimation framework.
3. Perform seismic scenario analysis to assess the relationship between building performance and the community capitals.
4. Demonstrate the results from the analysis on a dashboard to prioritize design and retrofit of buildings in a community that offer favorable trade-offs across the community capitals to enhance community resilience.

These objectives are satisfied through the development of a novel framework with two sets of measurements, articulated as objectives 1 and 2, that captures the number of buildings in each occupancy type contributing towards each community capital and their effects. The first set of measurements, captured at a community-level, formulates objective 1 which is achieved by identifying and evaluating the number of buildings in each occupancy type that influence each community capital through a scoring system for the building portfolio based on the keywords of the definition of each community capital. Additionally, adjustment factors are developed and employed to capture and balance the significance of the respective scores based on number of users. Next, the sum of each building type with respective adjustment factor and community capital score is normalized against the total number of buildings in the community. This process is then completed for the scenario event considered and then the results are plotted to portray the changes. The second set of measurements, performed at a building-level and then totaled, fulfills objective 2. This measurement is accomplished through evaluating the effect of building damage to respective community capitals. Built capital is measured as the number of buildings with extensive to complete damage normalized to total number of buildings. Social capital is measured as the dislocation rates due to building damage. Financial capital is measured as the repair cost/assessed building value lost normalized against values before event. Human capital is measured as fatality rates, injuries, post-traumatic stress disorder (PTSD) diagnoses amongst individuals, all normalized against total population. Political capital is measured as the accessibility (median distance) to resources such as school, hospital, fire station and government buildings from each zone by income status. The framework is then exemplified through the virtual testbed, Centerville [Ellingwood et al. (2016)], subjected to an earthquake scenario.

The outlook of this research may aid in remedying the situation faced by decision-makers in preparing for and responding to disaster. Finding a balance between critical factors such as the adjustment factors in measurement 1, governing features for each community capital, and data availability is also an important trade-off for widespread usability of the framework. Community resilience requires several different mediators, including individuals and researchers across many disciplines, the non-profit sector, public policy officials, and government officials at the local, state, and federal levels. Interpreting the community capitals collectively from different perspectives advances the state of knowledge in community resilience and supports risk-informed decision making.

1.2 Scope and organization

The framework developed focuses on buildings and building damage during a hazard event. Transportation, power and water supplies system were considered outside of the current scope, but their relationship with the community capitals should be investigated in future research. Populace characteristics used included fatality rates, injuries and post-traumatic stress disorder (PTSD) diagnoses amongst individuals. Data on health changes amongst age groups, disabled and institutionalized populace and other characteristics may be included as part of next steps. Additionally, economy in the community is tied to repair cost and assessed building values. This feature can be enhanced to include property value change, income, savings, profit or loss from business, self-retirement plans and more. Natural capital is excluded from both measurements and cultural capital is excluded in the second measurement due to insufficient data and relationships. As part of future work, factors affecting these two capitals such as environmental impact of buildings, attributes promoting the culture and orientation of community, should be explored.

This thesis is composed of four chapters apart from the introduction. A brief description of the chapters is as follows:

CHAPTER 2 reviews relevant literature on community resilience and its relation to the seven community capitals, models spanning engineering and social science discussing similarities, differences, and trade-offs concerning the present work and the novelty of this thesis and how it fits into and expands the research to date surrounding the topic.

CHAPTER 3 articulates the framework and methodology, including the newly proposed measurements of the community capitals and how it is integrated with the reframing of existing measurements of community capitals to provide a comprehensive view of losses and post-disaster impact on community that the more common single-building loss analysis models overlook. The development of the proposed community capital scoring system and adjustment factors used in the analysis is discussed extensively.

CHAPTER 4 exemplifies the framework using a virtual community testbed, Centerville, to illustrate the novel framework to measure community capital losses following an earthquake. The results from the analysis are presented and discussed.

CHAPTER 5 summarizes the contributions of this thesis and makes recommendations based on the results of Chapter 4. These recommendations should be shared with relevant stakeholders from multiple disciplines, including urban planners, engineers, decision-makers, and codes and standards committees. Furthermore, the limitations associated with the framework and future studies to explore is also provided.

Chapter 2: Literature Review

This chapter reviews the relevant literature on community seismic resilience assessment, including definitions of resilience, background on the seven community capitals, and existing measurements for community capitals and models spanning engineering and social science discussing similarities, differences, and trade-offs concerning the present work. This review provides the proper context for the novelty of this thesis and how it fits into and expands the research to date surrounding the topic.

2.1 Community resilience and the seven community capitals

Community resilience is defined as "the ability to adapt to changing conditions, withstand and rapidly recover from disruption due to emergencies" [PPD-8 (2011)]. This definition is further expanded in [PPD-21 (2013)] as "resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." In connection to these definitions, the current practice of retrofits and initial structural designs are intended to withstand disruptions from repercussions of previous disasters. However, the effects of disasters such as the 1994 Northridge earthquake, Hurricanes Katrina and Rita in 2005, Hurricanes Harvey and Maria in 2017, and Hurricane Michael in 2018, and more, suggest that this practice alone is not sufficient. Better disaster recovery policies and an improved design that includes functionality restoration time are required to support adaptation and rapid recovery from disruptions. This thesis builds on the community capitals framework proposed in Ritchie and Gill (2011) that purports that a community functions using seven capacities, e.g., seven community capitals: built, social, human, political, financial, cultural, natural [Ritchie and Gill (2011)]. The community capitals framework was developed as a direct response to the dominant use of the economic models to measure social welfare and is based on the principle of social justice [Flora (1998)]. Each community capital is outlined in Sections 2.1.1-2.1.7 of this thesis. This review aims to provide the context for linking all seven community capitals and the need to measure them to examine community resilience. Such examination of the community capitals should provide a holistic view of a community which may lead to the development of recovery policies and new design provisions that are more equitable and ultimately improve community resilience.

Actively engaging and advancing existing community resources to prosper in an environment that is subject to change, disruptions, and uncertainty is a sign of sustainability and community resilience. The concept of community resilience has been rendered in different academic fields that include psychology [Bonanno (2004), Masten (2001), Brown and Westaway (2011).], sociology [Alwang et al. (2001)], socio-ecological systems [Berkes and Seixas 2005, Adger et al. (2005), Folke (2006), Nelson et al. (2007)], and disaster research [Norris et al. (2008), Bruneau et al. (2003), Manyena (2006)]. An aspect of resilient communities is that the members intentionally develop a personal and collective capacity that are employed to counter and influence change, to sustain and rebuild the community, and to develop new trajectories for the communities' future [Magis (2010)]. The Federal Emergency Management Agency [FEMA, (2011)] suggests local and national responders build and maintain partnerships among emergency management, community sectors, and organizations; enhance social capital and civic activity to leverage and strengthen existing social infrastructure, networks, and assets and to empower local actions.

Although communities do not control all the conditions that affect them, for example, the industries influencing the local economy and climate change [Ahmed et al. (2004), Gibbon et al. (2002), Smith (2019)], community resilience is about individual and community's ability to respond to change [Healy et al. (2003). Folke et al. (2003)]. Therefore, developing resilience strengthens the community's ability to thrive in dynamic settings that are marked by unpredictability and uncertainty [Adger et al. 2005)]. Communities that respond to crises even through addressing the presenting issue engage their resources and generate resilience in the process to adapt and sustain in changing conditions [Adger et al. (2005); Flora and Flora (2004)]. Internal and external resources within a community are utilized to respond to changes. They exist in the natural world, in the people who live in the community, in the culture of the people, in the associations between the people, in the economy and infrastructure of the community, and in the political processes in which the community engages. These resources are referred to respectively as natural, human, cultural, social, financial, built, and political capital. Reiterated from Chapter 1, Table 2-1 provides definitions of each of the capitals utilized in NIST (2016) and adopted from Ritchie and Gill (2011). These capitals are not independent. For example, financial capital is dependent on social, cultural, human, political, natural, and built capital [(Hanushek, E. A. (2013), McCrea (2014), Pickett et al. (2004); Donoghue and Sturtevant (2007); Emery and Flora (2006)]. Similarly, built capital will be higher in communities with higher human, political, and financial capitals. These relationships are further explored in this chapter.

Table 2-1. Definitions of seven community capitals, Ritchie and Gill (2011)

Community Capital	Definitions
Built Capital	Buildings and infrastructure systems within a community
Social Capital	Social networks, associations, and the trust they generate among groups and individuals within the community
Human Capital	Knowledge, skills, health, and physical ability of community members
Political Capital	The ability to engage external entities in efforts to achieve goals and the ability/power to access and influence the distribution of resources
Financial Capital	Available financial savings, income, investments, and credit at the community-level that is instantly accessible
Cultural Capital	Language, symbols, mannerisms, attitudes, competencies, and orientations of local community members/groups
Natural Capital	Resources, such as air, land, water, minerals, oil, and the overall stability of ecosystems

Community resilience is shaped at different spatial and temporal scales, and thus measurements should capture these scales accordingly to develop preparedness in a community. In engineering analyses, the built environment is prioritized for investigating, informing, and developing mitigation plans. On the other hand, social science analyses often focus on human, cultural, environmental and social well-being [Aldrich and Meyers (2014), Stokols et al. (2013), Gill et al. (2016)]. Similarly, economic analyses focus on financial growth, labor productivity and potential through education [Pelinescu (2015)]. Ultimately, the seven capitals need to merge into a single interdisciplinary framework for a valid assessment of community resilience.

A study conducted by Walton et al. (2013), in a southern Queensland community experiencing change due to a coal seam gas (CSG) company development, illustrates community wellbeing and resilience in the context of rapid change. The work identified how the community members formed groups to represent, advocate, and engage with government and other local authorities to resolve issues such as conserving the natural capital of agricultural land and water resources for current and future wellbeing by drawing on their network and associations to acquire both monetary and material resources. In other words, the social, human, political and financial capital were employed to meet the community's needs. Other community service groups, such as neighborhood centers and church support services, leveraged their social, human and limited financial capital to advocate and support disadvantaged population groups (e.g., low income; disabled populations). Similarly, housing development companies and trades businesses had opportunities to increase their wellbeing from economic growth through training more employees and investing in properties. Developers drew on their financial, human and social capital, and political resources to obtain approvals for increased housing stocks. Tradespeople were in great demand but needed to increase their human capital to be compliant with stringent quality assurance and workplace health and safety requirements of the CSG companies, which placed a significant financial burden and risk on the local trade business's financial capital. This example demonstrates the importance and connectedness of all seven community capitals and how they are drawn upon in times of disruption.

From the review presented, it was concluded that community resilience is promoted through strengthening and engaging various resources, i.e. community capitals, by taking measures throughout the community. For this reason, the understanding of each community capital and how they play into the big picture individually and collectively is crucial. The following sections explore these prospects.

2.1.1 Built capital

Built capital defines the buildings and infrastructure systems within a community [Ritchie and Gill (2011)]. It is also referred to as the built environment, which includes buildings, integrated transportation systems, telecommunication facilities, water/ wastewater systems, and power generation and distribution systems. It is an indispensable part of a community; the individual and collective performance of buildings plays a critical role in the development of disaster resilience. According to Bartuska (2007), the characteristics required to examine built capital are inter-related in the context of a disaster. It includes everything humanly created, modified, or constructed, humanly made, arranged, or maintained. Consequently, its purpose is to serve human needs, wants, values, and, to mediate or change the overall environment for our comfort and well-being. All of these characteristics defines and shapes the built environment so that each component contributes either positively or negatively to the overall quality. Hence, loss of critical infrastructures, such as hospitals, transportation systems, and so on, in a post-disaster scenario can upsurge a community's vulnerability to future disasters.

With an increase in the number of weather and climate-related disasters in recent years [Smith (2019)] and an underestimation of the actual losses and their effects [Smith and Katz (2013)], adaptation to disasters will be a long-lived investment. Designing and constructing infrastructures that can cope with the changing climatic condition is expensive and problematic due to the uncertainties involved and the lack of a single climate model that encompasses the rate of climate change and their impacts [Hallegatte (2009)]. Design and assessment of adaptation and mitigation policies developed by distinct communities and decision-makers needs to include impact of climate change while investing in building and housing, water and transportation infrastructures, energy production, urbanization planning and so on [Hallegatte (2009), Nicholls et al. (2008), Nicholls and Leatherman (1996)]. Hence the inclusion of climate change while developing robust new infrastructures and assessing existing buildings for structural reliability promotes community resilience.

Disasters often jump-start initiatives and policy regulations in a community. Many scholars have discussed the 'window of opportunity' that exists after disasters that allow new policies and mitigation plans to pass while the impacts and risk of a disaster are fresh on stakeholders' and constituents' minds. Quite often recovery is discussed in terms of re-establishing normal routines, but while this may feel comfortable it guarantees the reestablishment of pre-disaster vulnerabilities. Rather, a resilient community builds back better. The reconstruction of Greensburg, Kansas after an EF5 tornado that levelled 95 percent of the 1.5-square-mile town is an example of building back better. The city was rebuilt to a world model for sustainable, environmentally friendly development that won state and federal grants and congressional appropriation for development and included incentive programs for businesses that reopen and set to green building standards [Paul and Che (2011)].

The example of Greensburg, Kansas was drawn to illustrate how built capital would lead to supporting other community capitals. Recognizing the relationship between built capital and other community capitals is valuable in organizing resources and articulating performance objectives for infrastructures. Disaster research suggests that built capital is generated through the application of financial, human, cultural, and social capital [Flora and Flora (2004), Goodman (2003), Ungar (2011)]. Brugmann (2009) describes how cities with no planning may reach high urban density, but the overall result is often inadequate. In this case, people with insufficient financial capital will be economically burdened and may be left to living in overcrowded and unhealthy buildings. Urbanists suggest that broadening housing, business, public, and private sectors would create a shared advantage and improve community resilience through built capital [Florida (2002), Alexiou (2006)]. Creating places of mutual interaction and services promotes participation, shared values, and a sense of trust as it leads to social capital development [Tierney (2014)]. Therefore, targeting buildings that produce these specific capitals, in this case social capital, and benefit other capitals will likely ameliorate the resilience of the community. The goal of this thesis is to identify and classify buildings that produce the other six community capitals, and to measure that generation through a novel framework.

2.1.2 Social capital

Aldrich (2017) detailed how social network influenced recovery more than the physical infrastructure following the Japan earthquake and tsunami disaster in 2011. Aldrich stresses the need for improving social and human capitals as they play a more prominent role than infrastructures in resilience and recovery. Social capital defines the trust generated among groups and individuals within the community as a result of social networks and associations [Ritchie and Gill (2011)]. Unlike the other types of community capital, social capital is only generated in the interactions between individuals and among groups. Hence, social capital does not simply exist, as infrastructure does, but requires action to establish and maintain. It is, therefore, one of the most crucial community capitals that is closely linked to and overlaps with other community capitals such as human, political and cultural capitals. As mentioned earlier, there has been an increase in disasters and with climate change the potential risk to a community and its occupants is on the rise. A typical response to these threats is to strengthen the physical infrastructure; however, doing so will not fully eliminate the risk or vulnerability. Experience from previous disasters suggests that communities with a robust social system experience less severe impacts when compared to communities with highly inequitable social systems [Aldrich and Meyers (2014), Aldrich (2017)]. In order to develop social capital as part of pre-disaster mitigation and post-disaster recovery, identifying its distribution, measurement approaches, mechanisms and its relationship to community resilience is necessary. This review outlines the types of social capital and its quantification in the literature and how it may be employed to improve or develop community resilience.

There are three main types of social capital: bonding, bridging and linking [Aldrich and Meyers (2014), Aldrich (2012b)]. Bonding social capital describes the connections among family and friends and result in tight bonds to a particular group and is associated with the social support and personal assistance required in times of need such as a disaster. It is often characterized by similarity in demographics, attitudes and available information and resources [McPherson et al (2001)]. For example, in the 1995 Kobe earthquake majority of individuals who were saved from under debris were by neighbors, and not rescue teams [Aldrich (2012a), Shaw and Goda (2004)]. The second type of social network is bridging social capital defined as acquaintances or individuals loosely connected that span social groups, such as class or race. This social capital is related to demographic diversity and providing information and resources that advance society. The "Gray Zone" Rehabilitation of Mano, a small neighborhood of 2,500 people located around 5 km west of downtown Kobe, is paradigmatic of people cooperating to create a better environment for the community through a long history of community development [Nakagawa and Shaw (2004)].

The third type is linking social capital that connects regular citizens with authorities and people with power and resources. These social networks are related to networks of trusting relationships between people who are interacting with formal or established power or authorities such as government and local organizations [Szreter, and Woolcock (2004)]. This type of social capital, however, overlaps the definition of political capital which is discussed in the following section.

Disaster studies suggest that communities with reliable social networks and relationships perform better across the disaster timeline from planning to rebuilding and recovery. For example, in March 2011, a 9.0 magnitude earthquake followed by a tsunami and a nuclear breakdown struck Tohoku, Japan killing 18,500 lives and over 160,000 people were forced to evacuate. A study done by Daniel Aldrich found that municipalities with higher levels of trust and interactions had lower mortality rates [Aldrich and Sawada (2015)]. Thus, higher social capital led to higher human capital. Similarly, following severe flooding in Kerala, India in August 2018, even before authorities could respond to rescue and relief, fishermen across the state were actively engaged in rescue operations using personal boats and means [Kerala Floods (2018)]. According to government estimates, a total of 4,537 people from the fishermen community participated in the rescue operation and managed to rescue more than 65,000 [Kerala Floods (2018)]. The proactiveness of community self-organization in Kobe, Japan also resulted in a quick recovery after the Kobe earthquake in 1995. These examples suggest that social ties and cohesion, i.e., social capital, are as important as other elements such as built and financial capital in the progression of community resilience.

In the aftermath of a disaster, a community may modify their views and activities as part of the rebuilding process. Distinguishing the social parameters in a community is imperative to recognize whether it is a place-based community or an interest-based community [Swyngedouw E (1997), Martson SA (2000)]. A place-based community consists of functional relationships based on socio-economic and political interactions as a result of the neighborhoods, ethnic backgrounds, and so on. Interest-based communities, on the other hand, are tied to the identity or some level of common perspective due to which they may engage in face-to-face interactions and other shared activities. Both types of communities are socially erected, and hence their needs and wants are based on mutual perspectives and interests with some internal structure/body that supports their goals and views. For example, many of these communities interact through formal events such as fundraisers, galas that are often inter-organized by clubs and other social firms. This thesis aims to capture buildings and organizations that build social capital through their services and functions, to integrate social outcomes alongside physically oriented mitigation options for risk-informed decision making. Many researchers locate social capital in resilient communities through surveys and onsite studies to understand and measure its distribution [Murphy, (2007)]. Measuring social vulnerability at the community-level and building-level provides insight in developing the built capital and its interconnectedness. Identifying and characterizing functions and dependencies of various social establishments based on individual and collective needs of the society is a key factor in the evolution of community well-being and sturdiness in the face of hazard events. Additionally, the key contacts and representatives need to be recognized for evaluation, coordination, and decision-making activities [NIST, (2016)].

Existing works of literature and studies suggest the importance of social capital; however, the metrics to measure the objectives associated with it is still at odds. The two ways of measuring social ties are by attitudinal and cognitive approach and behavioral manifestation. In attitudinal and cognitive approach, surveys and questionnaires are used in capturing agreement to the level of trust or commitment to society (for example, questions like "do you trust your neighbors?"). Most frameworks developed for social capital in community resilience are based on measuring behavioral manifestation. It includes surveys on interaction and cooperativeness amongst people (for example, "how often do you contact your friends and family?") [Aldrich and Meyers (2014)]. Voter participation, the number, and roles played by non-profit organizations, voluntary associations, and religious organizations are other variables that can be used to measure social capital [Mayunga (2007), Cutter et al. (2010)]. These measures ensure that there are networks to nurture connectedness among the people living in the community which is very important in an emergency.

Fedders (2018) developed indices to quantify the importance of social infrastructures in community resilience on a pre-disaster, disaster and post-disaster time scale. Three indices namely, organization social capital index, building social capital index, critical infrastructure interdependency index are used in the estimation of the level of importance of an organization, the structure housing the organization, and the interdependencies between the social organization with critical facilities. His work illustrates that designing social infrastructure to higher levels can preserve on average of 45% of social capital generated by the organization and 60% of the building's social capital during an MCE (maximum considered earthquake) scenario. His work also draws on the relationship between a structure and the organization within it. This thesis aims to further this particular aspect of his work and elaborates by bringing in the other five community capitals.

Traditional social science studies identify five major institutions as fundamental to all communities: family, education, government, religion, and economy – each of which is overlapping and interdependent. Recent conceptualizations include broader notions of each institution, identifying additional types of social institutions. There are eight social institutions: family and kinship, economic, government, health care, education, community service organizations, religious organizations and others that support belief systems, and media. Generally, these institutions satisfy the basic needs of society by defining dominant social values, socializing individuals, establishing patterns of social behavior, and providing roles for individuals. In doing so, institutions contribute to the welfare of society by preserving social order and supporting other institutions. Social institutions are a major producer of social capital, and there is a strong interconnectedness with cultural, human, financial, and political capitals.

As a result, infrastructures that facilitate these social institutions require special attention to strengthen the community as a whole [NIST, (2016)]. Household dislocation is one of the repercussions on the social institutions following a hazard event and is adopted as measure for social capital in this thesis. Household dislocation rate is defined as the percentage of households in a community that are displaced due to loss of housing habitability and short-term shelter needs [FEMA, (2003)]. It should be understood that in reality the dislocation rate is governed by factors other than building damage. For example, a family may relocate temporarily even if the building is not damaged, but the neighborhood is affected producing concerns of safety and wellbeing.

Furthermore, it is also important to note that the presence of social capital does not always imply a positive outcome. Unity and trust within a community could result in a cooperative approach to emergency planning and management from which all the members gain benefits. However, if the internal social capital would not necessarily translate into group networking amid communities, other communities may be considered as outsiders and looked at with suspicion [Fukuyama R (2001)]. Although social capital constitutes a significant function in a community, to facilitate it, the existence of other factors is essential.

2.1.3 Human capital

NIST (2016) adopted Ritchie and Gill (2011) to define human capital as the "knowledge, skills, health, and physical ability of community members". Human capital has one of the most substantial ties to each of the other capitals because it is community members who get things done and the reason, we have communities. Ideas, attitudes, willingness to participate and the power of working together is how human capital affects a community. Mixing individual capacities and identifying, using, and combining resources can benefit both the individual and the community. It is also developed through other community capitals such as social capital [Coleman (1988)] and leads to the development of financial and political capital [Riley (2014)]. As a result, measuring and developing human capital is vital in building a foundation for community resilience.

Disruptive events lead to loss of human capital directly and indirectly. Knowledge and skills of community members facilitate the ability to think in new ways and are also the basis of developing leaders in the community. Health and physical ability of community members are important factors psychological and physical well-being are vital to productive activities and actions in the event of a disaster. Mcdermott et al. (2016) used a socio-technical systems analysis[1] to combine human and physical infrastructure development in the context of a critical infrastructure renovation. The socio-technical approach captured the social factors of community resilience and focused on human capital development which as discussed lays a path for development of other community capitals. In their work, environmental, infrastructure, financial and organizational factors were linked to human capital aspects of community reliance on multiple scales to identify causal relationships between individual micro-scale indicators of infrastructure and social program development, and aggregate effects of human capital development.

Goodwin (2003) characterizes human capital by a socio-environmental view of individual and collective resources. Employing these features develops productive capacities of individuals which may be both inherited and acquired through education and training. However, human capital and social resilience combine the socio-environmental aspects of a place with the psychological aspects of social network support which have not been addressed in a multidisciplinary study [Berkes and Ross (2013)].

[1] a methodology that supports assessment of multiple complex factors across all layers of a complex societal construct using sets of tools derived from both systems-of-systems engineering and participatory design disciplines

Human capital is also an indicator of the educational levels, vulnerable population, livelihood capabilities. These indicators can be exercised to measure losses and also to recognize areas of weakness that could be eliminated through proper community resilience planning and development [Mcdermott et al. 2016]. Human capital has been studied by macroeconomists to determine the long-term effect it has on economic growth (financial capital). The role of education in the development of human capital and consequently on financial capital were analyzed by Baro (2001) in a panel around 100 countries and was concluded that educational background would be complementary with new technologies, hence an important role for the diffusion of technology. Another study by Pelinescu (2015) revealed a positive relationship, statistically significant between GDP (gross domestic product) per capita and innovative capacity of human capital (evidenced by the number of patents) and qualification of employees (secondary education).

Human capital at the individual level is composed of the knowledge, skills, and abilities one possesses along with the beliefs, desires, and intents one uses to make a living which when combined with any individual vulnerabilities, form the resilience of an individual. Human capital is equipped and maintained by physical and institutional infrastructures, as well as the education and healthcare systems in the region [Folds and Thompson (2013)]. Maintaining and producing human capital in a region is determined by complex interactions of these systems. A successful city is highly dependent on human capital assets and social capital assets.

Human capital development is highly dependent on the education systems in the early years and the health systems in the early and later years. These combine to maintain a healthy and appropriately trained labor force in a city’s economy. Therefore, access to healthcare, education, and jobs form the core of social sustainability and resilience, along with the beliefs, desires, and intents that engage individuals to participate in those systems in productive ways.

A significant question of city redevelopment must then address not only the physical infrastructure but also the human capital redevelopment [Mcdermott et al. 2016].

The concept of human capital development and the combined socio-environmental and psychological views are an important area of research for future resilient communities. Integration of human capital, social networks and institutional supports within models of built and financial capitals are a first step taken in this thesis. Here, loss of human capital is captured through morbidity rates including post-traumatic stress disorder (PTSD), fatalities, and injuries, and is discussed in Chapter 3 as to how it fits into the proposed framework.

2.1.4 Political capital

Political capital defines the access to resources and the ability/power to influence their distribution; also, the ability to engage external entities in efforts to achieve goals [Ritchie and Gill (2011)]. Political capital connects community development with government resources and private investment. It reflects the people's capacity to express themselves and to participate as agents in their community [Goodwin (2003)]. It is also the community's ability to access public resources or impact the rules and regulations that affect its day to day functioning and is often mediated through elected leaders and officials [Vidich and Bensman (1968)]. Jacobs (2007), considers the presence of political capital as having the ability to influence decisions, engage state and federal agencies in the projects, discover new funding sources and possess the leverage to achieve community goals. The third type of social capital, 'linking social capital,' defined by Aldrich and Meyers (2014) connects regular citizens with authorities/ people with power which is an overlap with the definition of political capital. Social systems of trusting relationships between people who are interacting with formal or established power or authorities such as government and local organizations form this type of political capital [Szreter, and Woolcock (2004)].

Financial and social capital accrues political capital which assists in linking community building, government assistance, and private investments [Turner (1999)]. Community groups need to have political empowerment, even though this may be difficult to acquire. For this reason, the community must understand its political influences, such as the role of the local, county, state, and the federal government to bring forth desirable outcomes. A review of community and economic development (CED) efforts in rural communities by Fey et al. (2006) concluded that in 95 percent of the communities, new connections were made between the community and various levels of government as a result of the CED efforts. This suggest that having an engaging financial and social relationship has an active role in strengthening the community's political capital.

A southern Queensland community experiencing change due to a coal seam gas (CSG) company illustrated community wellbeing and resilience in the context of rapid change [Walton et al. (2013)]. The study identified how the community members formed groups to represent, advocate, and engage with government and other local authorities to resolve issues such as conserving the natural capital of agricultural land and water resources for current and future wellbeing by drawing on their social, human, political and financial capital. Developers, housing development companies and trades businesses all depended on financial, human and social capital, and political resources to bring forth desirable outcomes.

2.1.5 Financial capital

Financial capital defines the savings, income, investments, and available credit at the community-level [Ritchie and Gill (2011)]. It facilitates economic production, though it is not by itself productive, refers instead to a system of ownership or control of built capital. [Goodwin (2003)]. Financial capital describes the sum of financial assets and physical property that make up household wealth such as money in savings accounts, life insurance, pensions, housing, consumer durables, business investments. Each represent different types of wealth and differing levels of accessibility in times of need. Assessing household incomes, property values and investments in a community can be used to measure financial capital [Peacock et al. (2010)]. Access to credit and debt is also an element in the measurement of financial assets, and the size of the debt burden will have an impact on the level of household vulnerability. Severe financial consequences come with many risks, including the loss of income from as job loss, or large, unexpected expenses from property damage, or from treating long-term illness. Community members or organizations with the highest net worth (total assets minus liabilities), or with the ability to borrow or access credit, are best able to continue to meet their consumption needs when confronting adverse shocks. While the poor are less likely to have direct financial assets, they need access to insurance or credit to protect against shocks from disasters. The asset-poor and the income-poor are not necessarily the same groups [Morrone et al. (2011)]. For example, those with higher financial capital can use it to raise their human capital through education and consequently, social, cultural and political capital. On the other hand, asset-poor households can rely on friends and family for financial support and may not be as vulnerable as those without anyone to count on (provided such connections exist). This would mean that having good social ties and networks also alters how much financial capital is available in an emergency.

Investing in financial capital is beneficial to a community, but an appropriate and equitable plan should be developed. When proper planning on how to deal with a financial crisis is not prepared, a community may go through boom and bust phases. A study on Johnstown, Pennsylvania, a small, rural and isolated town assessed the revenue and sales projections; facility space needs for employment projections, and issues affecting the local business climate to learn financial trends. The authors suggested that data could be used as an objective by local planners and governments to prioritize projects and how to invest and build financial and built capital for the future [McGrath and Vickroy (2003)]. They highlighted the importance of measuring the current financial situation of a given community as well as looking at the projected future outcomes when working on community economic development efforts. Since the amount of available financial capital dictates the growth of built capital and consequently, other community capitals planned and strategic efforts should be taken by community groups. The direct and indirect financial costs of a disaster involve addressing the distribution of financial resources, economic programming and ensuring that interventions are cost-effective, the economic development of the post-disaster infrastructure and increasing the diversity of economic resources. A community's post-disaster economy is essential not just for recovery, but also for mitigating future disaster risks. Proactive investments to rebuild the economy, therefore, is of utmost importance [Patel et al. (2017)].

2.1.6 Cultural capital

Cultural capital refers to language, symbols, mannerisms, attitudes, competencies, and orientations of local community members/groups [Ritchie and Gill (2011)]. Pierre Bourdieu, a late-twentieth-century French sociologist, developed and popularized the term cultural capital and first used it in his written work with Jean-Claude Passeron in 1973 ("Cultural Reproduction and Social Reproduction"). It was then further developed as a theoretical concept and tool of analysis in his landmark study 'Distinction: A Social Critique of the Judgement of Taste', published in 1979. Cultural capital reflects how a community perceives the world, their values, and their assumptions about how things fit together. Symbols in language, art, and customs are a representation of this. Culture creates the people's attitude and perception of life events and sets the social rules related to power and influence in a community [Flora and Flora (2004)]. Aspects of culture necessary to community resilience include community members' belief in their ability to protect the well-being of the community, their ability to survive and thrive through change, and their belief in their ability to develop the necessary capacity to become resilient. This intricate pattern of ideas, emotions, and observable/symbolic manifestations tend to be expected, reinforced, and rewarded by and within a particular group as a result of the cultural orientation.

Cultural capital is the collection of knowledge, behaviors, and skills that demonstrate one's cultural skill, and thus one's social status or standing in society. Bourdieu (2018) stated that cultural growth was used to reinforce class differences, historically and in the present day; different groups of people have access to different sources and forms of knowledge, depending on other variables like race, class, gender, sexuality, ethnicity, nationality, religion, and even age. Cultural capital exists in three forms: the embodied state, objectified state, and institutionalized state. "The embodied state is in the form of long-lasting dispositions of mind and body. The objectified state is in the forms of cultural goods (pictures, books, dictionaries, instruments, machines), which are the trace or realization of theories or critiques of these theories and problematics. An institutionalized state is a form of objectification that must be set apart because as will be seen in the case of educational qualifications, it confers entirely original properties on the cultural capital that is presumed to guarantee." [Bourdieu (1986), page 241-258].

Community resilience is developed through a collective effort to accomplish specific community objectives. Collective action requires participation and leadership from throughout the community which is dependent on the cultural orientation. The extraordinary work of a singular individual or group of individuals is insufficient [Berkes et al. (2003), Harris et al. (2000)]. Collective action is more efficacious when people from diverse and autonomous groups work together, and when people know what organizations and people are essential, as well as how to accomplish their objective [McAdam et al.(1996),Tarrow (1998)]. Examples of metrics include the extent to which community leaders facilitate collaboration between groups to work on community objectives; the extent to which community decision-making processes engage diverse perspectives and reflect cultural differences; and the extent to which people from diverse groups share supports, resources, knowledge, and expertise when confronted with change [Magis (2010)].

In socio-ecological literature, community members' local and traditional knowledge, as well as their experience and understanding of the community, confer on them an important role in the community's well-being [Berkes et al. (2003), Pritchard and Gunderson (2002)]. Their contributions are seen as complementary to those of conventional management and their inclusion in management institutions is advocated [Folke et al. (2003)]. Hence, though external forces impact the community, the community can influence its well-being and take a leadership role in doing so [Ahmed et al. (2004), Davis et al. (2005), Jackson et al. (2004)].

Additionally, Bourdieu (1986) points out that cultural capital exists in a system of exchange with economic and social capital. For example, with economic capital, access to prestigious educational institutions can be bought where valuable social capital is fostered. Eventually, it leads to acquiring elite forms of cultural capital. In turn, both the social and cultural capital accrued at an elite educational institute can be exchanged for economic capital, via social connections, knowledge, skills, values, and behaviors that help one attain high-paying jobs [Cole (2019)]. On this ground, Bourdieu observed that cultural capital is used to facilitate and enforce social divisions, hierarchies, and ultimately, inequality. However, it is essential to recognize and value cultural capital that is not classified as elite. Ways of obtaining and displaying knowledge and what kinds of cultural capital are considered necessary differ among social groups. For example, the critical roles of how knowledge, norms, values, language, and behaviors differ across regions of the US and even across neighborhoods that urban kids must learn and abide in order to survive in their environments.

2.1.7 Natural capital

Natural Capital is defined as resources such as air, land, water, minerals, oil, and the overall stability of ecosystems [Ritchie and Gill (2011)]. In other words, it is made up of the resources and ecosystem services of the natural world [Goodwin (2003)]. Preservation, development, and enrichment of natural capital is essential as the first and foremost need of human beings is to survive in an environment that sustains life. Consequently, basic physical requirements, such as air, water, food, shelter, and clothing need to be considered for productive and sustainable development of capital stock. Depletion of most natural resources is as a result of economic growth and activities such as production, consumption, and distribution which must be supplemented with resource maintenance [Goodwin (2003)]. Having said that, it is crucial to measure the capital stock so that it can be sustained, strengthened, managed and consequently adapted to building community resilience.

For a community to adapt, withstand and rapidly recover from disruptions, the natural resources, and environmental conditions need to be evaluated. Natural capital is influenced by individual and collective human activities but also presents opportunities and limitations on human, social, cultural, and financial capitals [Machlis and Force (1997)]. During the process of developing community resilience, community members are working with the community's resources, and the investment of resources in the community increases the productivity of current resources and generates new resources [Magis (2010)]. Land planning and air quality indexes play a significant role in the mitigation and recovery process of a community. Metrics such as how well people understand the opportunities and limitations of the natural environment in and surrounding their community; economic, social and environmental impacts on natural resources management; access of various groups to the community's natural resources when evaluated gives erudition required for policy recommendations.

As part of natural resource management, operationalizing policies designed to control the variability of resources, for example, timber, through equilibrium-centered, command-and-control strategies may be employed [Folke et al. (2006)]. Another example is a community–forest relations through policies tied to community stability that maintains the specific structure and functioning of the community despite the change. It considers that natural resource agencies could provide stability in forest-dependent communities through stable employment in the forestry sector and with consistent flows of timber products from forest lands [Donoghue and Sturtevant (2007)].

Natural Capital is excluded from the analysis in this thesis due to insufficient data related to classifying organizations that facilitate natural capital growth. Future work could bring natural capital into analysis through measuring environmental impacts of buildings and infrastructures using platforms such as ATHENA Impact Estimator for Buildings (2017). Estimated values for fossil fuel consumption, global warming potential, acidification potential, human health criteria, eutrophication potential, ozone depletion potential, and smog potential obtained can then be used to develop environmental impact indexes that may be used for policy recommendations of building units both temporary and permanent [Badeaux (2018)].

The present work builds off of the established literature reviewed in this chapter to propose a novel, quantitative framework for measuring community capital generating through a community's building portfolio. The proposed framework model can be used by decision makers and city planners in maintaining and improving community resilience. Chapter 3 illustrates the framework step-by-step and how it fills the gap in current state-of knowledge integrating single-building analysis to a community-level measurement.

Chapter 3: Community Capital Framework

In an effort to fill the gaps in the literature, a novel framework that captures the relationship between buildings and organizations throughout a community was developed and is presented here. Existing loss estimations focus on single building analysis which does not capture important dynamics and collective losses that occur at a community-level. The framework presented here operates at the community-level leveraging the seven community capitals to achieve a comprehensive view of how losses occur in a community after a disaster.

The framework developed in this research is shown in Figure 3-1. Community characteristics, including the building portfolio and population data (e.g., total population, number of households, number of users per occupancy type) is obtained and input into the model. Once inputs are obtained, a two-tiered approach is taken to measure losses: one at the building-level and one at the community-level. The two-tiered approach enables a holistic view of losses by incorporating the effects of disaster on all seven community capitals through novel measures. This approach examines a community across the disaster timeline, both pre-disaster and post-disaster, computing the change in each community capital before and after a hypothetical disaster scenario. This framework produces a dashboard of metrics following each hazard simulation, allowing for risk-informed decision making.

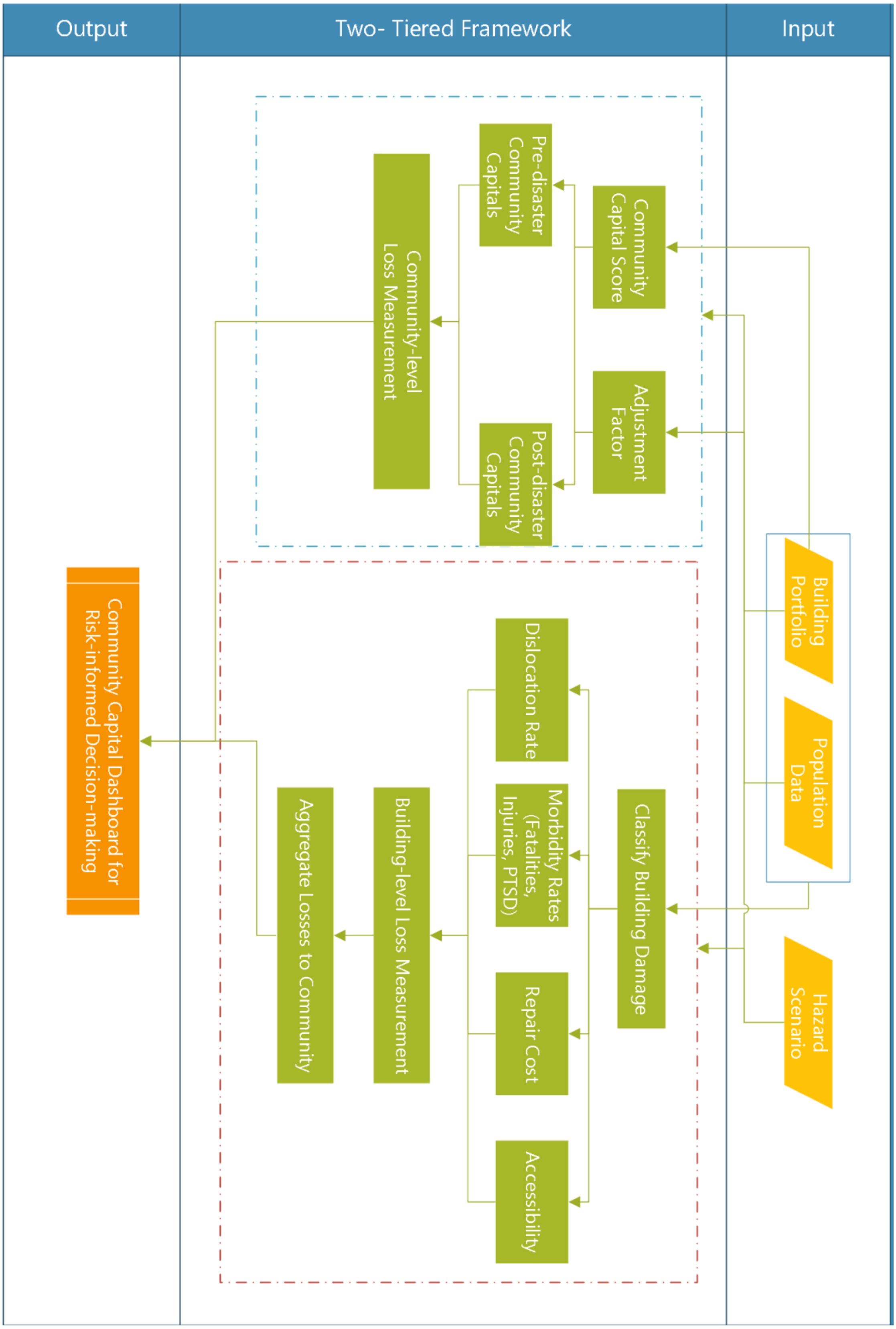

Figure 3-1. Community capital loss estimation framework

Referring to the middle and left section of Figure 3-1, the community-level loss measurement relates building occupancy type to community capital; the number of buildings in each occupancy type are then used to quantify the influence building damage has on each community capital. Referring to the middle and right section of Figure 3-1, the building-level loss measurement evaluates losses at a building-level using existing methods identified through the literature review, including dislocation rates (social capital), morbidity rates (human capital), accessibility changes (political capital), and repair costs (financial capital). The results from the two-tiered measurements are integrated to obtain a comprehensive view of the impact of the disaster scenario on the community. As output, a community capital 'dashboard' is developed to present trade-offs for supporting decision makers in understanding how changes to characteristics of the community can enhance or inhibit community resilience. A dashboard, as opposed to a composite index or score, enables the user to see the trade-offs across multiple criteria that influence community resilience, as opposed to a single (composite) measure that may be too vague for a decision maker to understand.

This novel framework aims to advance the current state of knowledge of organizational loss. This chapter presents the different elements involved in the development of these measurements step-by-step first at the community-level and then at the building-level. The methodology of and justification for combining these elements along with the supporting literature is also presented.

3.1 Community-level loss measurements

The first part of the two-tiered approach, performed at the community-level is presented in detail in Figure 3-2. First, a community capital score and adjustment factor are computed using the building portfolio, population data and hazard scenario inputs. Second, the community-level loss measurements are assessed by making comparisons across the disaster timeline for each of the community capitals.

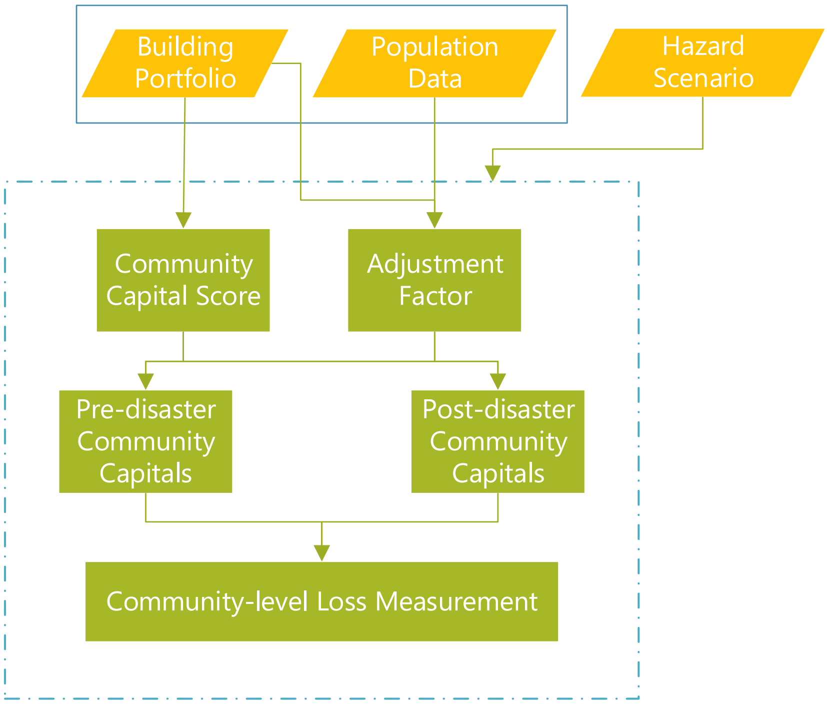

Figure 3-2. Community capital loss estimation framework at community-level

The building portfolio is integrated with population data to develop the community-level community capital measurement, CC_j, expressed as

$$CC_j = \sum_{i=1}^{15} \frac{n_i \cdot a_i \cdot s_{ij}}{N} \tag{1}$$

Where,

j = a specific community capital, namely, built, social, human, cultural, political, financial, and natural

i = a specific occupancy type, namely, Single-family dwellings (SFD), Multi-family dwellings (MFD), Retail, Government, Commercial, Entertainment, Storage, Religious, Civic, Recreational, Industrial, Education, Hospital, Fire station, Utility.

n_i= number of units in occupancy type, i

a_i= adjustment factor for occupancy type, i

s_{ij}= score for occupancy type, i and community capital, j

N = total number of buildings in the community across all occupancies

As expressed in Eq. (1), the number of units in each occupancy type, n_i, is multiplied by the respective adjustment factor, a_i and score, s_{ij}, where the score is presented in Table 3-1 for each occupancy type. This product is normalized against the total number of buildings in the community, N. This estimate is summed across all occupancy classes to obtain each community capital value. This is performed for both pre-disaster and post-disaster to obtain the differences in values for all seven community capitals and can be plotted to depict changes or reported via dashboard to present totals.

Table 3-1. Community capital score, s_{ij}

Occupancy type	Built Capital	Social Capital	Human Capital	Cultural Capital	Political Capital	Financial Capital	Natural Capital
SFD	1	0.67	0.25	1	0	1	0
MFD	1	1	0.25	1	0	0.67	0
Retail	1	0.67	1	0.6	1	1	0
Government	1	0.67	1	0.6	1	1	0
Commercial	1	1	1	0.8	0.67	1	0
Entertainment	1	0.33	0.25	0	1	1	0
Storage	1	0	0	0	0	0.33	0
Religious	1	1	0	1	1	0.33	0
Civic	1	0.67	0.5	0.2	0.33	0.33	0
Recreational	1	0.67	0.5	0	0.33	0.33	0
Industrial	1	0.67	0.5	0	0.33	1	0
Education	1	1	1	1	1	0.67	0
Hospital	1	1	1	0	1	1	0
Fire station	1	0.67	1	0	1	0.67	0
Utility	1	0	0	0	0	1	0

The development of Eq. (1) involves two distinct variables: score, s_{ij}, and adjustment factor, a_i, for accounting for the role of occupancy class in the community, and for the number of users for each occupancy class, respectively. The following section provides the quantitative formulation of these specific measurements derived from criteria obtained through the literature review in Chapter 2.

3.1.1 Community capital score

The score, s_{ij},was developed for each community capital and occupancy type based on the definition of the community capitals utilized in the NIST Community Planning Guide [NIST, (2016)] and adopted from Ritchie and Gill (2011). Occupancy type is used here to classify buildings by the type of usage. For example, churches are categorized as Religious occupancy type. Residential buildings are classified as residential, but split into two categories, single family dwelling (SFD) or multi-family dwellings (MFD), based on the number of units to control for the number of users to the building. Table 3-2 provides the criteria, from the definitions presented in Ch. 2, used to develop the scores. Scores range from 0 to 1 with each criterion receiving equal weight. A scale of 0 to 1 was used throughout for consistency across community capitals since each capital has a different number of criteria associated with its definition. Community capital score, s_{ij}, can be expressed as

$$s_{ij} = \frac{Number\ of\ criteria\ satisfied}{Total\ number\ of\ criteria} \tag{2}$$

Table 3-2. Community capital scoring criteria

Type of Capital	Criteria	Score for each criterion
Built	buildings	1.0
Social	networks, associations, trust generated	0.33
Human	knowledge, skills, health, physical ability	0.25
Cultural	language, mannerisms, attitudes, competencies, orientations	0.20
Political	access to resources, ability to influence resource distribution, ability to engage external entities in efforts to achieve goals	0.33
Financial	savings, income, investment	0.33
Natural	stability of resources such as air, water, land, minerals and oil	-

The score for each criterion shown in Table 3-2 is computed using Eq. (2). For example, built capital gets a score of one since buildings are being analyzed here, and thus exactly match the single criteria listed in the built capital definition. There are three criteria in the definition of social capital, namely, networks, associates, trust generated, thus each is assigned a score of 0.33.

Table 3-1 provided the score of each occupancy type for the respective community capital using the criteria in Table 3-2. The reasoning for each value shown in Table 3-1 is portrayed in Figures 3-3 through 3-8 and explained as follows. If an occupancy type satisfies all criteria mentioned for the specific community capital it gets a score of 1 else the total score is obtained by multiplying the number of criteria satisfied to the score. For example, SFD satisfies two of the three criteria for social capital, network and trust generated, so the score will be $2 \times 0.33 = 0.67$. Similarly, MFD satisfies all three criteria, therefore the score will be $3 \times 0.33 = 1$.

For built capital the criteria used is assessing whether the structure considered is a building or not as shown in Figure 3-3. If the criteria are satisfied, a value of 1 is assigned else 0.

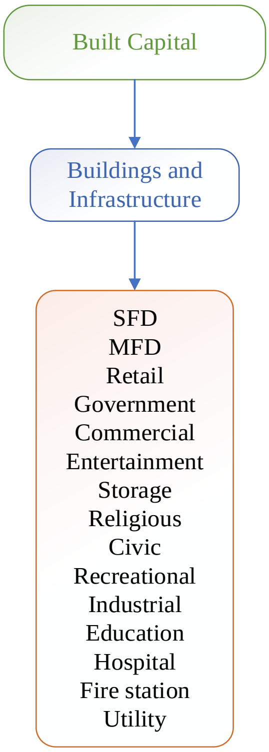

Figure 3-3. Occupancy types satisfying built capital criteria

As introduced earlier, single-family dwelling (SFD) and multi-family dwellings (MFD) are classified separately because of the significant social and policy differences between these two types of residential occupancies. This separation also simplified the calculation since the number of SFD units is often orders of magnitude higher in a given community compared to the number of MFD units. Adjustment factors were developed to account for the different number of units and different number of users for the different occupancy types; adjustment factors are discussed in the following sections.

As shown in the Figure 3-4, there are three criteria for social capital each with score of 0.33. The Oxford English Dictionary defines social networks as a network of social interactions and personal relationships where trust is defined as “firm belief in the reliability, truth, or ability of someone or something” generated as a result of formal and informal relationship. Duhaime’s Law Dictionary [Duhaime, L. (n.d.)] defines social association as a “form of organizational structure for a defined group of individuals, for a religious, scientific, social, literacy, educational, recreational or benevolent or commercial purpose”. Based on these understandings, assessments are made to estimate whether each occupancy type contributes to each criterion. For example, single-family dwellings are considered to foster strong relationships and generate trust since it is usually persons of a single family that occupy these buildings. Similarly, for multi-family dwellings, all three criteria are assumed applicable given the larger number of households residing in the individual building. Government, Commercial, Religious, Education and Hospital were assumed to satisfy all three criteria as organizations within these occupancy types promotes both formal and informal relationships. Entertainment buildings were assumed to develop only networks whereas Civic buildings such as public libraries, museums, and town halls develop both networks and associations, for example, membership activities in the organizations may provide connections and informal ties between members [Aldrich and Meyers (2014)]. For Retail, Recreation, Industrial and Fire station, network and association are assumed to be applicable due to the nature of interactions between individuals in these occupancy type where trust generated is assumed to be small to negligible.

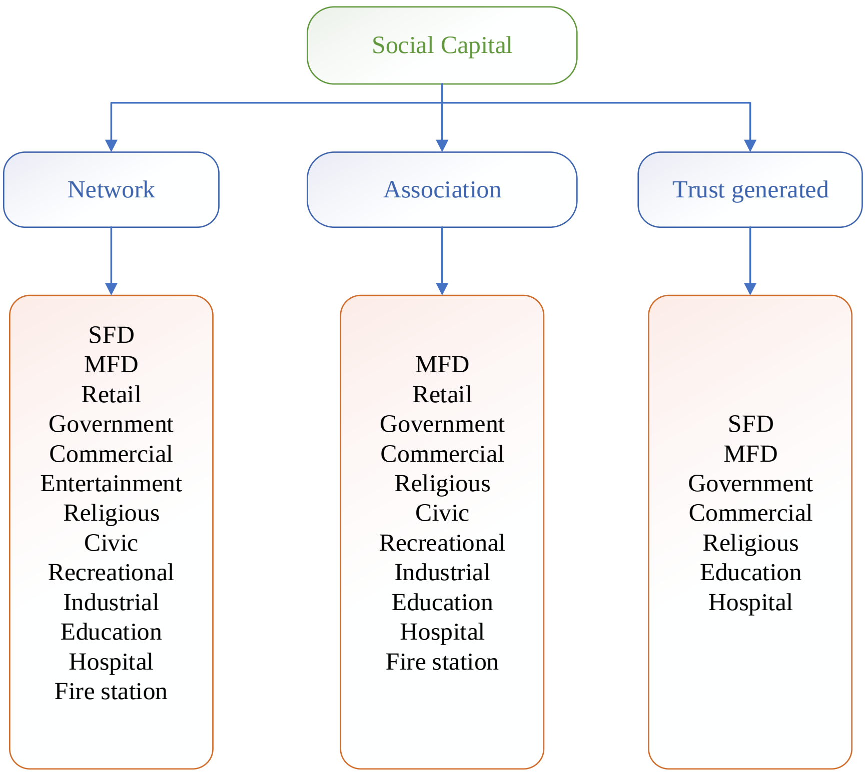

Figure 3-4. Occupancy types satisfying social capital criteria

Figure 3-5 represents the occupancy types contributing towards human capital through four criteria where each gets equal weights of 0.25. Each occupancy type is closely examined to understand which criteria is satisfied. For example, it is assumed that human capital is developed in Retail through knowledge, skill set, health and physical ability as one's current knowledge and skill set progresses with training and as part of being employed and it provides income that supports the individual to have means to healthcare, consequently maintain physical ability. On the same note, Government, Commercial and Fire stations were assumed to contribute all four criteria like Retail. Schools provide education thereby producing knowledge and developing skills, as well as providing a nourishing environment to maintain health and physical ability. On the other hand, Hospitals develop all four criteria similar to the previously mentioned and additionally provides healthcare to the community thereby contributing to the physical ability of the population. SFDs and MFDs provide shelter and hence were assumed to contribute towards health criteria. Civic and Industrial were assumed to satisfy the knowledge and skills criteria whereas Recreational classes were assumed to satisfy health and physical ability by providing space for activities such as exercises, sports, and games.

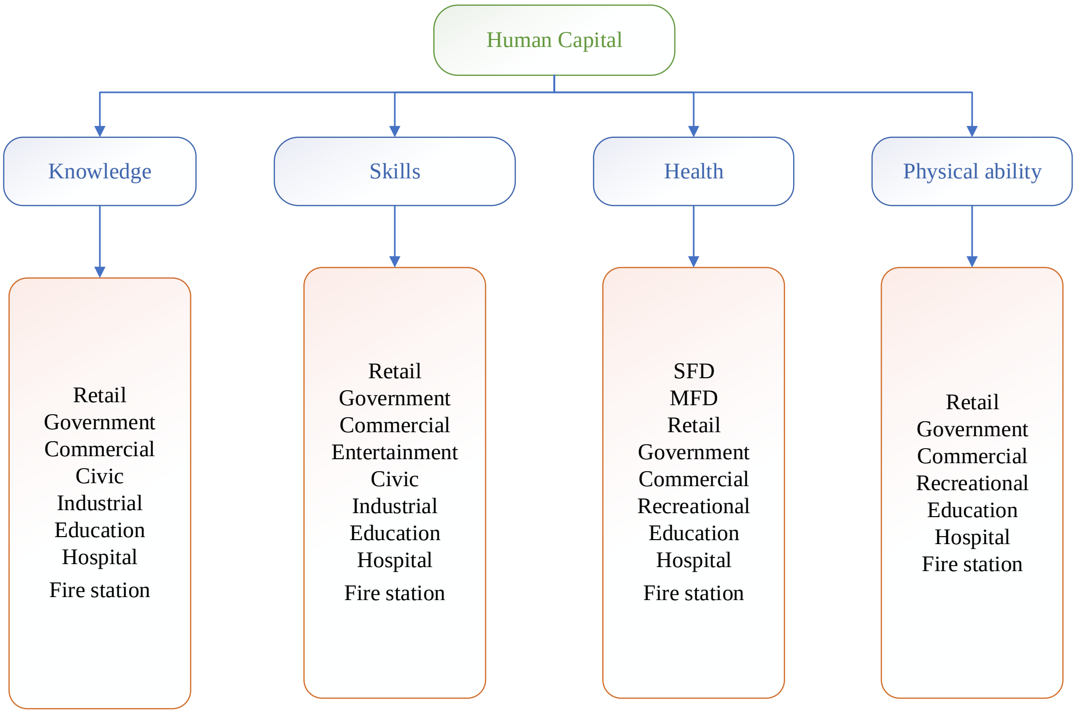

Figure 3-5. Occupancy types satisfying human capital criteria

Figure 3-6 provides the occupancy types contributing towards each of the five criteria for cultural capital. The Oxford English Dictionary defines mannerism as “a habitual gesture or way of speaking or behaving”. Competencies is defined as a set of skills, values and principles that acknowledge, respect and work towards optimal interactions between individual and the various cultural and ethnic groups that an individual might come in contact with [Understanding Cultural Competency. (n.d.)]. Cultural orientation is a predisposition to think, feel or act in a way that is culturally determined and defines the basis of differences among cultures such self-identity, interpersonal relationships, communication, resolving conflict [Gilbert, K., & Rosinski, P. (2008)]. The Oxford English Dictionary defines attitude as a settled behaviour or manner of acting, as representative of feeling or opinion. Symbols, although important for understanding cultural capital at a community-level, is not considered here due to complications in linking to buildings. Evaluations based on this understanding is performed to recognize occupancy type satisfying each criterion.

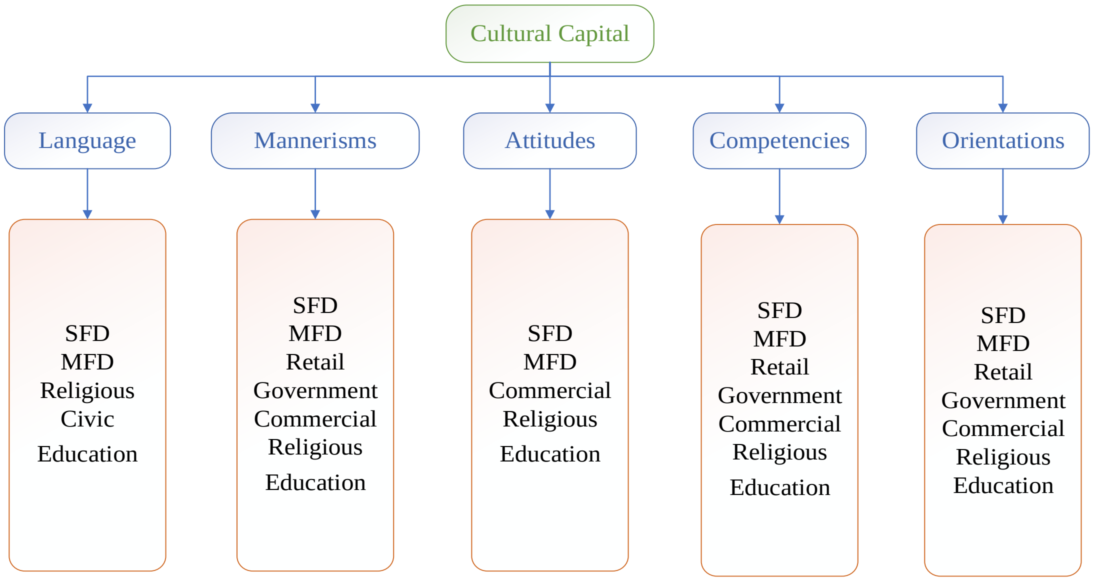

Figure 3-6. Occupancy types satisfying cultural capital criteria

For example, occupancy types such as SFD, MFD, Religious, Education were assumed to satisfy all five criteria since these occupancy classes have the most influence on the development of cultural capital by setting the aspects of culture necessary to community resilience including community members' belief in their ability to protect the well-being of the community [Flora and Flora (2004)].Commercial satisfies mannerism, attitudes, competencies and orientation as each of these are required to work in the commercial sector and is subsequently developed overtime. For Government, mannerism, competencies and orientation are developed as it facilitates collaboration between groups to work on community objectives, challenges and decision-making processes to engage diverse perspectives. Whereas for Retail, mannerism, competencies and orientation are developed through work environment and may lead to development of interpersonal relationships.

Figure 3-7 represents the occupancy types contributing towards each criterion for political capital following the same evaluation steps mentioned for previous community capital where all three criteria are examined for each occupancy type. For example, faith-based establishments serve a way to stimulate local activity, increase interactions, and facilitate organizational activity and hence were assumed to satisfy all three criteria. Similarly, education and guidance are considered for schools as a resource and may serve as emergency shelters during disasters. Likewise, occupancy types such as Retail, Government, Entertainment, Storage, Religious, Education, Hospital, Fire station and Utility were assumed to satisfy all three criteria

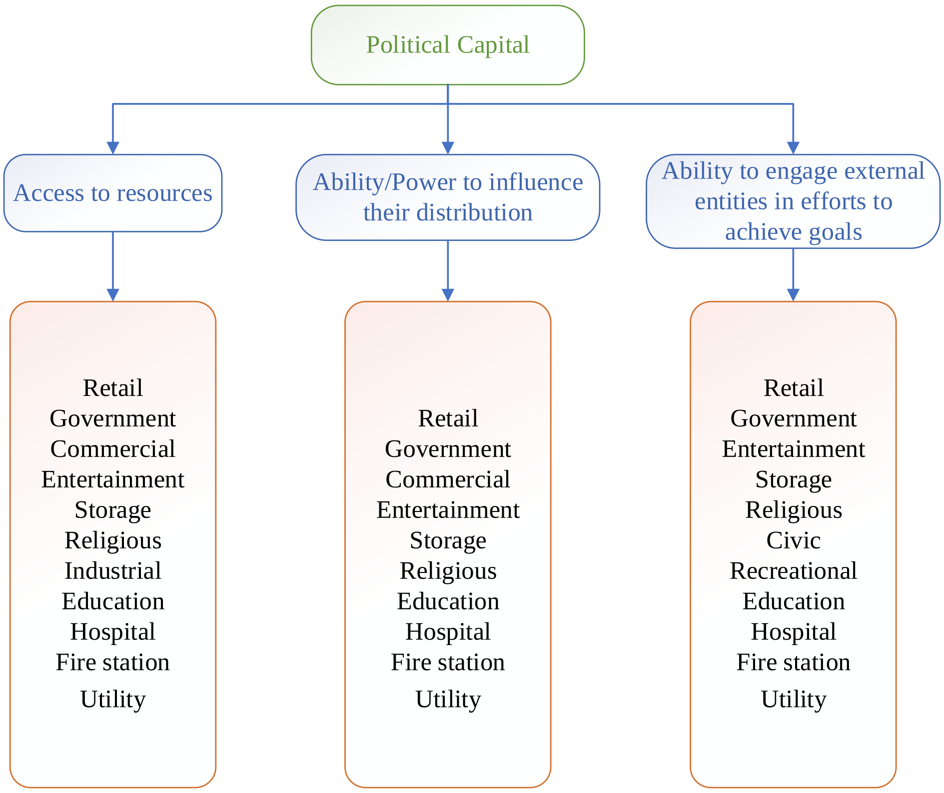

Figure 3-7. Occupancy types satisfying political capital criteria

Financial capital has three criteria, shown in Figure 3-8, where each occupancy type is examined following the evaluation steps mentioned for previous community capitals. For example, SFD may satisfy the savings and investments criteria as the building on its own is an asset, and the resident's income is a contribution towards the overall financial capital. Similarly, Government satisfies all three criteria as the pay of each employee can be seen in forms of income and savings, the organization within the building is also an investment as it produces goods or supplies services and fulfills needs of the community.

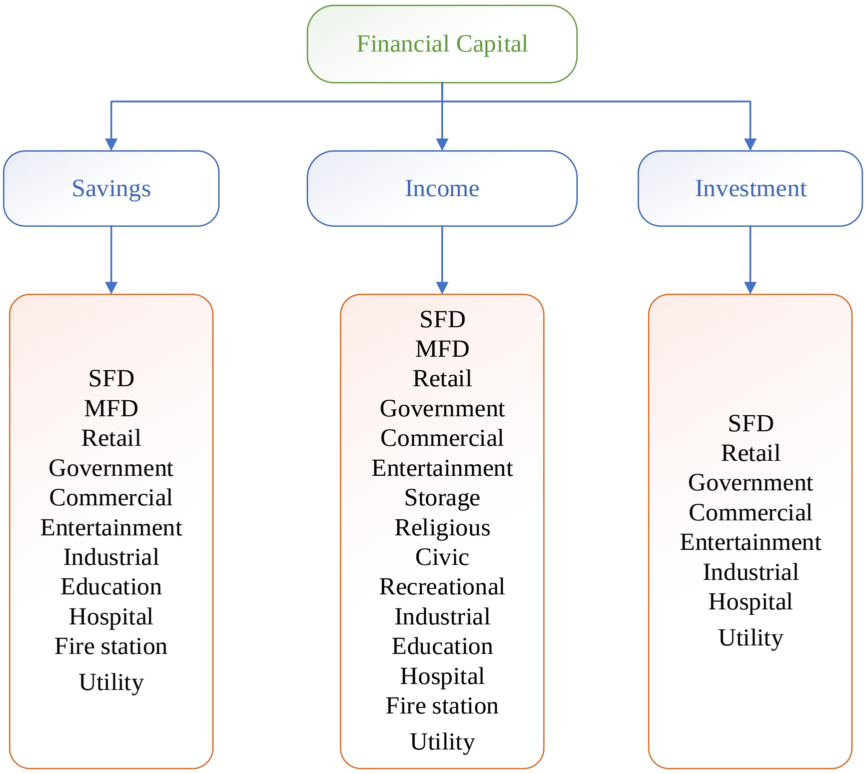

Figure 3-8. Occupancy types satisfying financial capital criteria

3.1.2 Adjustment factors

Adjustment factors, a_i are developed based on the number of users of a building to capture and balance the significance and number of buildings in each occupancy type across the community. As mentioned in the earlier section, while SFD has a significant impact on community capital, the large number of SFDs in a community can overshadow the impact of other occupancy types. Therefore, an adjustment factor was developed to help account for not only the number of buildings with that occupancy type in the community, but also the number of users or number of people impacted by that occupancy type in the community. For example, only one household uses a single-family home, although there are many single-family homes in the community. Conversely, entire communities will use a single hospital, although there may be only one hospital in the community. Adjustment factors, a_i can be simply expressed as:

$$a_i = \frac{Number\ of\ users\ per\ building\ unit}{Average\ household\ size} \quad (3)$$

In Eq. (3) the numerator differs by occupancy class as the estimation of number of users per building is dependent on the occupancy type. Table 3-3 presents the details and references used for estimating number of users per building for each occupancy type. For example, for SFD and MFD, the number of users is the U.S. average household size (2.54) based on the U.S. Census Bureau (2018) whereas for Commercial occupancy, a crude population estimation of 3.5 occupants per 1000 sq. ft at an average time of the day is assumed to estimate the total number of users per building. The number of users per building is then divided by the household size (2.54) to normalize the number of users to a residential unit. The rationale for normalizing by average household size is to control for the significantly higher number of SFD to other occupancy types. For Industrial Structures, number of users was assumed to be the average number of workers which varies depending on the facility and its operation, therefore is specific to the community. Crude population estimate was not used for Industrial Structures as a higher portion of the building probably contains machinery or equipment and is also dependent on the facility, and as a result would be an overestimation of the number of users. The average number of workers per industries is between 4 and 500 [U.S. Census Bureau (2018)].

Table 3-3. Number of users per building by occupancy class

Occupancy type	**Number of users per building**	**Reference**
SFD, MFD	Average household size (2.54)	U.S. Census Bureau (2018)
Commercial, Education, Fire stations, and Government	Crude population (3.5 occupants per 1000 sq. ft)	Assumption
Hospital	Crude population (3.5 per 1000 sq. ft) + U.S. average number of overnight stays (7.6%)	Assumption, Lucas and Benson (2018)
Industrial	Average number of workers depending on the facility (4 – 500)	U.S. Census Bureau (2018)

3.2 Building-level loss measurements

This section presents the second tier of loss measurements performed at the single building-level using traditional methods that build off the loss estimation literature which has focused on measures of deaths, dollars, and downtime. This work advances the traditional loss measurements by relating each one to different community capitals. Figure 3-9 presents the building-level loss measurement approach adopted here. Cultural capital and natural capital are excluded from this measurement due to insufficient data and relationships.

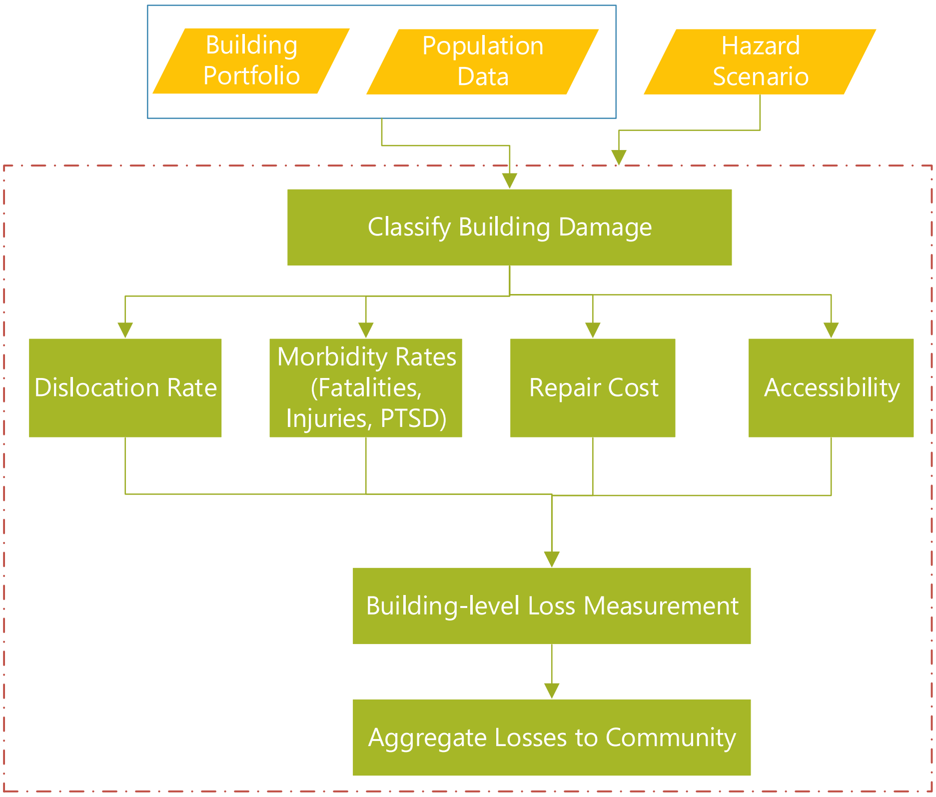

Figure 3-9. Community capital loss estimation framework at building-level

A hazard analysis is carried out on a selected community. From there, building damage is classified into damage states, and used to directly assess the built capital where built capital is measured here as the number of buildings experiencing extensive and complete structural damage. Dislocation rates are calculated as a function of building damage state and used for measuring the loss in social capital; fatalities, injuries and post-traumatic stress disorder

(PTSD) are also calculated as a function of building damage states and used to evaluate loss in human capital; access to resources is used to measure political capital. These measurements capture the building-level losses which are then aggregated to obtain the community-level loss. It should be noted that there is more than one method of measurement for each of the community capitals discussed. The methods selected in this study are based on the literature review of community capitals measurements and are dependent on building damage. The following sections provide the computations for each of the measurements chosen for this research.

3.2.1 Number of structurally damaged buildings

Damage states can be defined as distinct and sequential categories of damage to structural and non-structural components of a building causing significant differences to threat of life safety, usability and repair costs and process. Building damage states are described as 0= None, 1= Slight, 2= Moderate, 3= Extensive and 4 = Complete, where the structural damage occurs at DS3. Damage estimation resulting from these four damage states are then used to produce probability of a building being in any of the four damage states under a given hazard scenario.

Here, built capital loss, N_D is measured as the number of buildings with extensive to complete structural damage, D_i normalized to the total number of buildings in the community before the hazard scenario, N. The extent of structural damage is computed as the collective number of buildings in Damage States 3 and 4 after an earthquake scenario. Similarly, the extent of the collapse is computed as the number of buildings in Damage State 4 after an earthquake scenario.

$$N_D = \sum_{ds=3}^{4} \frac{D_i}{N} \tag{4}$$

3.2.2 Household dislocation rates

Household dislocation is one of the repercussions following a disaster and can be caused due to several reasons, including building damage, neighborhood impacts, concerns of safety and wellbeing, access to alternative shelters or homes, and factors resulting from socio-economic, political and environmental impact [Sapat and Esnard (2016)]. Household dislocation rate is defined as the percentage of households in a community displaced from their home during or immediately after a disaster[FEMA, (2003)]. Household dislocation, along with other factors such as economic or insured loss, fatalities, injuries, emotional distress, evacuation, and loss of quality of life are historically used to measure disaster impact on communities [Weber and Peek (2012)]. These factors are mostly caused as a result of disproportionate social status patterns and unsafe built environment (built capital). Household dislocation is also responsible for a significant portion of economic loss generated by disasters [Peacock et al. (2015)]. Sutley et al. (2017) use household dislocation as part of a seismic hazard analysis that aimed to capture the effect of earthquake disasters on physical infrastructures and the social system. From the review, it can be concluded that the dislocation rate can be used to measure the loss of social characteristics following a disaster.

Household dislocation rates due to building damage are used to measure social capital loss. To determine the dislocation rate, or, the number of households dislocated, $n_{ds,i}$ in each archetype in Damage state 3 and 4 is multiplied by the corresponding number of units, n_i, and then summed.

$$DR = \sum_{ds=3}^{4} \sum n_i \cdot n_{ds,i} \tag{5}$$

3.2.3 Fatalities, injuries, post-traumatic stress disorder

Fatalities, injuries, and posttraumatic stress disorder (PTSD) are used here to measure the impacts on the population and are the result of physical damage as well as social characteristics such as age, ethnicity, health, and wealth status. Low-income households and households with low socioeconomic status are the most vulnerable groups to injury, fatality, displacement, and PTSD [Fothergill and Peek (2004), Cutter et al. (2003), Weber and Peek (2012)]. Extensive building damage and building collapses results in the majority of death and injuries [Shoaf et al. (1998)] whereas building damage and damage to personal property have been linked to higher rates of PTSD in affected populations [Sharan et al. (1996), Ramirez et al. (2005)]. If the infrastructure is older and/or of poor quality the vulnerability of the associated population is much worse [Cutter et al. (2003)]. Additionally, the morbidity indicators along with dislocation rate were used in Sutley et al. (2017) as part of a seismic hazard analysis that aimed to capture the effect of earthquake disasters on physical infrastructures and the social system.

Morbidity counts such as fatality rates, injuries, PTSD diagnosis rate are computed here based on building damage. The mean value for each morbidity rate is provided in Table 3-4. The critical injury rate and fatality rate were adopted from HAZUS MH-2.1. The PTSD diagnosis rate was taken as the severe injury rate in HAZUS (in which severe injury is less serious than critical injury) due to a similar rate being observed in the literature [Sutley et al. (2017)]. The morbidity counts, MC, were determined by multiplying the morbidity rates, $R_{M,ds}$, in Table 3-4 by the household size (2.54) for SFD and MFD, and; crude population size (3.5) for the retail, commercial, government, hospital, school, and fire station; average population size for each building for industrial. Morbidity count is expressed as:

$$MC = HS \cdot \sum_{ds=1}^{4} R_{M,ds} \cdot \sum n_i \cdot n_{ds,i} \tag{6}$$

Table 3-4. Morbidity rate by damage states (mean value) [Sutley et al. (2017)]

Damage state	Critical injury rate	Fatality rate	PTSD diagnosis rate
1	0.0000005	0.0000005	0.000005
2	0.0000003	0.0000003	0.0003
3	0.00001	0.00001	0.001
4	0.03	0.05	0.2

3.2.4 Accessibility ratio

Political capital, as the definition suggests, is measured through the access to resources. Since there are overlaps in political capital and social capital, it often leads to understanding the sustainability of livelihoods and local economy [Bebbington and Perreault (1999)]. Politica capital helps in understanding the social inequalities and the political ecology of a community through roles of capital formation at different geographic scales in promoting community member's access to different forms of capital, both directly and through engaging with state, market, and other civil society actors [Bebbington and Perreault (1999)]. Although access to the resource would include health care to an immediately available asset, this thesis models the access to buildings that embody organizations such as school, hospital, and fire station to the community members and is measured through geographical distance.

The median distance from each neighborhood in a community is measured to the mentioned resources (hospitals, schools, fire stations) and calculated before and after a hazard event to assess political capital. The post-disaster value focuses on whether any of the said resources where damaged and if so, which is the next closest option.

3.2.5 Repair cost due to building damages

Often the financial impact of a disaster is estimated through direct losses, which include building repair, reconstruction, reconstruction cost, losses in business as a result of property loss, and other incurred losses. Loss estimation tools such as HAZUS MH-2.1 and FEMA P-58 [FEMA (2012)] are used by researchers to study the loss patterns and distribution in various structures. They are also adopted into structural analysis software engines to make it a consistent and straightforward process for practicing engineers, stakeholders, and other associated authorities. This thesis evaluates the repair costs incurred due to building damages as loss measure for financial capital. The U.S. average cost per sq. ft. ($153/ sq. ft.) is used to estimate the total building value [NAHB, (2017)]. Repair costs incurred due to building damages are used as an estimated financial capital loss.

Ensuring a community is resilient before a disaster can only be achieved by identifying and quantifying key factors in each building that supports the community's well-being alongside with communicating the values of these factors to stakeholders and decision makers. Employing the traditional loss measurements alongside the novel score system to measure community capital loss advances disaster resilience research by providing a new perspective to loss estimation models. The next chapter exemplifies the framework discussed herein by demonstrating it on a testbed and discussing the benefits of encompassing community capitals in building loss estimation for developing community resilience.

Chapter 4: Exemplifying the Framework

A case study is performed on a virtual community, Centerville, to demonstrate the proposed framework. The hypotheses involved in the development of the framework is thus tested to ascertain the community capital generated through a community's building portfolio.

Centerville is one of the testbeds developed as part of a National Institute of Standards and Technology (NIST)-funded Center of Excellence for Risk-based Community Resilience Planning. The center is designed to allow research teams to initiate, test, and modify essential resilience models and algorithms. Details about the center are described elsewhere [Ellingwood et al., (2016)]. Figure 4-1 portrays the map of Centerville, a virtual city of moderate size located in a Midwestern state with approximately 50,000 in population. The city is roughly rectangular with an 8 mi. by 5 mi. plan. There is a railway line that follows the east side of the Rock River that runs through the center portion of the city.

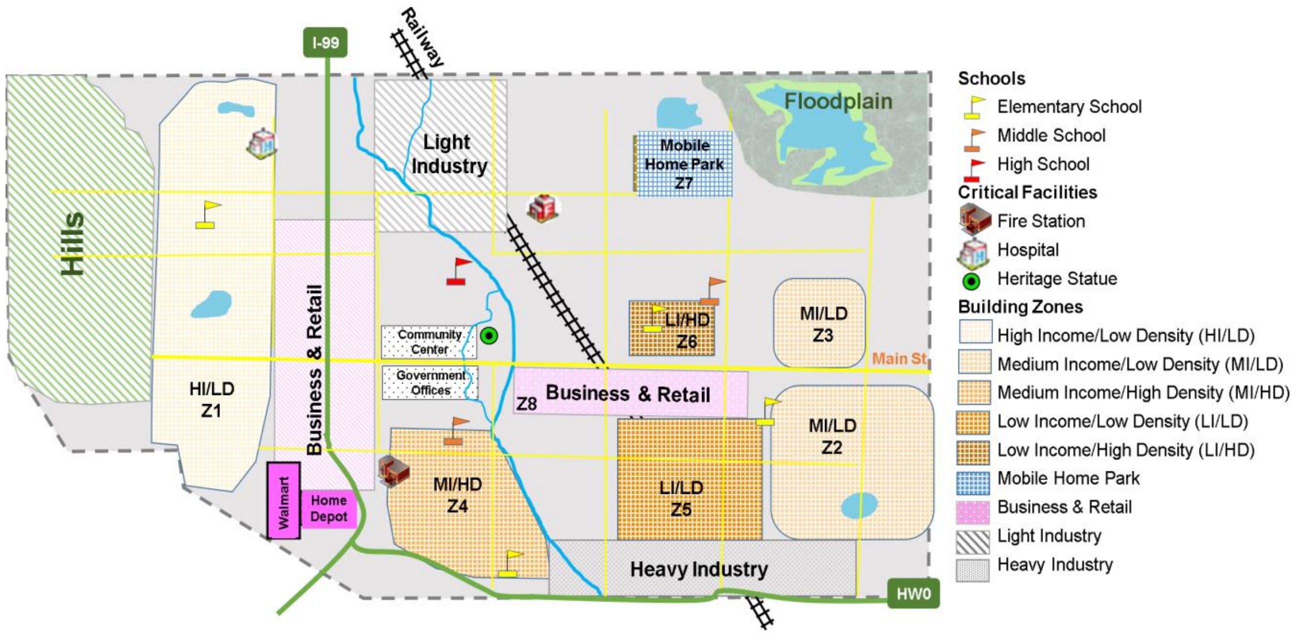

Figure 4-1. Map of Centerville

The building portfolio consists of 16 building archetypes that include residential, commercial, and industrial occupancies, as well as critical facilities including hospitals, fire stations, schools, and government offices. These 16 archetypes, in terms of occupancy and structural systems, are used to assemble the building inventory of Centerville. Centerville is comprised of diverse residential and non-residential buildings that facilitate commerce and the livelihood of the community. There are seven residential neighborhoods, with a mix of high income/low density (HI/LD) and middle income (MI) or low income (LI) residential areas, and a mobile home park. There are two commercial/retail zones, which includes two large box stores in a newly developed area in the southern part of the city that employs approximately 250 to 300 people. Local government facilities are in the old center of town, near the river. There are two relatively large industrial facilities. A regional hospital serves Centerville and the surrounding county. There are four public elementary schools, three middle schools, and one community high school. Details of the building portfolio are provided in Table 4-1 and Table 4-2.

Table 4-1. Centerville building portfolio

Zone	Building Type	Number of dwelling units per building	Number of buildings	Floor Area (sq. ft.)	Occupancy type	Number of households per zone
Zone 1	W2	1	2000	2400	SFD	4246
	W3	1	50	3200	SFD	
	W4	1	2196	2400	SFD	
Zone 2	W1	1	767	1400	SFD	2267
	W2	1	700	2400	SFD	
	W4	1	800	2400	SFD	
Zone 3	W1	1	300	1400	SFD	800
	W2	1	300	2400	SFD	
	W4	1	200	2400	SFD	
Zone 4	W1	1	2567	1400	SFD	4767
	W2	1	1000	2400	SFD	
	W5	48	25	36000	MFD	
Zone 5	W1	1	1856	1400	SFD	1856
Zone 6	W1	1	700	1400	SFD	4396
	W5	48	77	36000	MFD	
Zone 7	W6	1	1352	1620	SFD	1352
Zone 8	S1	NA	16	50000	Retail	800
	RC1	NA	11	50000	Retail	
	RM1	NA	30	25000	Retail	
Zone 9	S1	NA	29	50000	Retail	
	RC1	NA	13	50000	Retail	
	RM1	NA	46	25000	Retail	
	S2	NA	6	125000	Retail	
Zone 10	S3	NA	25	100000	Industrial	125
Zone 11	S4	NA	45	500000	Industrial	

Table 4-2. Centerville building resources

Occupancy ID	Building Type	Number of dwelling units per building	Number of buildings	Floor Area (sq. ft.)	Occupancy type	Number of households per zone
ES1	RM3	NA	1	100000	E School	7
ES2	RM3	NA	1	100000	E School	
ES3	RM3	NA	1	100000	E School	
ES4	RM3	NA	1	100000	E School	
MS1	RC3	NA	1	100000	M School	
MS2	RC3	NA	1	100000	M School	
HS	RC3	NA	1	100000	H School	
Fire1	RM2	NA	1	10000	Fire1	2
Fire2	RM2	NA	1	10000	Fire2	
HC	RC2	NA	1	120000	HC	1
Govt	RC1	NA	8	50000	Govt	8

The framework developed here and presented in the previous chapter, is hazard-generic, however for demonstration, the hazard considered for this thesis is seismic and it is necessary to establish the type of seismic hazard analysis used. There are two types of seismic hazard analysis: probabilistic and deterministic analyses. Probabilistic seismic hazard analysis (PSHA) represents an aggregation of numerous earthquakes (all possible events) in an area characterized by a cumulative distribution function (cdf) defining the probability of exceedance for specific seismic intensities, for example 10% probability of exceedance in 50 years. Probabilistic seismic hazard maps for any location in the U.S are available at USGS seismic tools which provides peak ground acceleration or peak ground velocity or spectral parameters at specific return periods. PSHA is suited for designing individual facilities as intensities can be represented at a probabilistically specified level of the seismic hazard in codes and other regulatory documents [Adachi and Ellingwood (2010)]. Deterministic hazard analysis represents the seismic intensity with spatial variations for a specific earthquake in terms of magnitude and epicenter with respect to the location of the building. PSHA is chosen here as it considers all possible scenarios and computes the rates of scenarios combining it to a ground motion above a threshold to determine probability of exceedance.

The seismic hazard analysis performed by Lin and Wang (2016) was adopted in this research: a hypothetical scenario earthquake with *Mw* 7.8 and an epicenter located approximately 40 km southwest of Centerville. Centerville is assumed to be on Site Class B soils and the ground motion attenuation model by Campbell (2003) and the capacity spectral method were used to determine the intensity measure at each building site. Spectral displacement S_d was considered as the intensity measure for determining the damage of structural and drift-sensitive non-structural components, and spectral acceleration S_a for acceleration-sensitive non-structural components and building contents. Building characteristics such as occupancy, structural type, construction material, number of stories, plan area, and year built were used to map seismic fragility functions using the HAZUS-MH database [FEMA, (2003)].

4.1 Building-level loss measurements

This section calculates the building-level loss measurements presented in Section 3-2 for Centerville under an earthquake scenario.

4.1.1 Measuring built capital loss by assessing number of damaged buildings.

As detailed in Chapter 3, Eq. (4) is used to calculate the built capital loss in Centerville resulting in 64% of building experiencing either severe or complete damage. Important resources such as hospital, fire station, school and government buildings were structurally destroyed i.e. DS4. More than half of SFD, MFD and retail buildings were also structurally destroyed. Table 4-3 provides the summary of buildings damaged to DS3 or DS4 states.

Table 4-3.Number of structurally damaged buildings by occupancy type

Occupancy type	Number of structurally damaged buildings	Total buildings
SFD	9,483	14,788
MFD	77	102
Retail	138	151
Industrial	50	125
School	7	7
Fire station	2	2
Hospital	1	1
Government	8	8
Total	9,763	15,184

4.1.2 Measuring social capital loss through household dislocation rates

Table 4-4 outlines the household dislocation rate in the residential sector computed using Eq. (5). The vast majority of the households in MFD were dislocated. Recall, each MFD building has 48 units, therefore damage to one MFD impacts more household, at a time than damage to one SFD, thereby resulting in additional social capital loss.

Table 4-4. Household dislocation rate by housing type

Occupancy type	Dislocated household	Total household	Dislocation Rate
SFD	9,483	14,788	64%
MFD	3,681	4,896	75%

4.1.3 Measuring human capital loss through morbidities

Eq.(6) and Table 3-4 are used to evaluate the morbidity due to building damage. The overall critical injury is estimated to be around 506 which is 1 % of the total population (50,000). Fatality is estimated to be 843 which is approximately 2% of the total population, whereas the number of persons diagnosed with post-traumatic disorder is estimated to be 3,393 which is 7% of the total population. It should be noted that the number of people suffering critical injury may also be suffering from PTSD. 1.1% of fatality, 0.68% of critical injury, and 4.6% of people suffering PTSD occurred in SFD. This result suggests approximately 9% human capital loss in Centerville which is significantly high.

4.1.4 Measuring political capital loss through accessibility

Accessibility, presented in Table 4-5, is computed as the median distance to resources such as school, government and hospital from each zone on a disaster timeline. However, as noted before there was complete loss of access to these buildings suggesting the harsh impact on political capital for Centerville, therefore Table 4-5 only presents proximity to resources pre-disaster. The high-income zone, Zone 1, has high access to at least one elementary school, middle and high school. In addition, it is also closest to the hospital. Middle income zones such as Zones 2, 3 and 4 all have at least one school near, and are moderately close to fire stations. The hospital is farthest for Zone 2 but moderately near Zone 4. Low-income zones, such as Zone 5, 6 and 7, have moderate to close access to all resources. Loss of access to all available resources suggests a complete political capital loss in the community and has a severe impact on all zones regardless of proximity prior to the disaster.

Table 4-5. Access to resources by geographical distance from each zone

Zone	Proximity to Resources (miles)									
	Elem. School	Elem. School	Elem. School	Elem. School	Mid. School	Mid. School	High School	Fire1	Fire2	Hospital
Zone 1 (HI/LD)	0.89	3.98	4.91	3.67	2.54	4.30	2.33	2.56	3.05	1.37
Zone 2 (MI/LD)	5.81	1.95	0.87	3.02	3.27	2.53	3.57	3.77	3.32	5.69
Zone 3 (MI/LD)	5.20	1.22	0.95	3.39	3.13	1.37	2.95	3.82	2.40	4.90
Zone 4 (MI/HD)	3.43	2.46	2.75	0.79	0.79	3.42	2.06	0.63	2.80	3.76
Zone 5 (LI/LD)	4.72	1.50	1.01	1.70	1.98	2.50	2.61	2.42	2.71	4.75
Zone 6 (LI/HD)	3.97	0.21	1.23	2.57	1.97	1.10	1.71	2.71	1.37	3.75
Zone 7 (mobile park)	3.95	1.51	2.48	3.96	3.05	0.61	2.09	3.82	1.13	3.43

4.1.5 Measuring financial capital loss through repair cost due to building damages

As described in Chapter 3, damage ratios were used to evaluate the repair cost of each occupancy type. Total building value was evaluated using U.S. average cost per sq. ft. ($153/sq. ft.).The highest repair cost, presented in Table 4-6, was seen in single family residential buildings followed by the industrial buildings. SFD buildings are often in large number in communities and therefore contributes the majority of loss. SFDs are also investments to the home owners, therefore has a major impact on community’s financial capital.

Table 4-6. Repair cost by occupancy type

Occupancy type	**Repair cost (USD)**	**Total building value (USD)**
SFD	1,059M	4,384M
MFD	130M	569M
Retail	312M	946M
Industrial	882M	3,875M
Education	25M	124M
Fire station	1M	3M
Hospital	6M	19M
Government	22M	62M
Total	2.44B	9.98B

4.2 Community-level loss measurements

The current practice of highlighting individual buildings to improve structural reliability and enhancing community resilience is inadequate. Each building is part of a bigger system that involves important elements of a community defined here as the community capitals. The first set of measurements in the framework, demonstrated here, aims to capture the importance of measuring loss from community-level using the scoring system Section 3-1.

Adjustment factors computed for Centerville using Eq. (3), is outlined in Table 4-7. The number of units and floor area per building for each occupancy type required for calculating number of users for respective building is obtained from Table 4-1 and 4-2. As discussed in Chapter 3, the average household size, 2.54, is based on the U.S. Census Bureau (2018). Since the number of for Industrial Structures is dependent on the facility it was assumed to be 300 for Centerville. Thus, the variables in Eq. (3) are obtained, and adjustment factors are calculated, where the values are then rounded to the nearest whole number. For example, for SFD, the number of users or the household size (2.54) is multiplied by the number of units (1) and then divided by 2.54. Similarly, for MFD, the number of users or the household size (2.54) is multiplied by the number of units (48) and then divided by 2.54. In the case of Centerville, the adjustment factor for hospitals is 1,661 whereas for SFD it is 1. This is to adjust the importance of one hospital relative to approximately 15,000 SFDs in Centerville. The number of users for Industrial Structures was assumed to be 300 for Centerville.

Table 4-7. Adjustment factors

Occupancy type	Adjustment factor
SFD	1
MFD	48
Retail	56
Government	445
Industrial	3
School	394
Hospital	1,661
Fire station	14

Table 4-8 provides the score for each occupancy type for the respective community capitals pre-disaster and Table 4-9 provides the score for post-disaster using adjustment factors shown in Table 4-7. The scores of all occupancy type are then totaled for each community capital for both before and after the disaster to estimate community capital loss. SFD scores higher than MFD for social capital even though MFD has a higher criterion score than SFD (refer Table 3-1), this is due to the large number of SFDs. Similarly, Education scores higher than Hospital for built, social, human, and political even though both have the same criteria score as per Table 3-1. This is to point out that the number of buildings in a given occupancy type is a controlling factor not just because of number of units but also due to the impact on the large group of people. Therefore, the scores are meant to be used as a tool to capture the community-level loss of individual capitals from purely a building perspective and possibly aid in developing retrofitting strategies and other community developments. Of course, these numbers are not definitive since there are other factors in play for each of these capitals. For example, political capital involves the ability to influence the distribution of resources, the buildings only act as a medium for such developments to take place, an individual or a group of people is who makes it happen. Consequently, it can be said that this part of the framework captures the indirect losses to community capital due to buildings. For example, if a school is damaged, in addition to loss of access to education services and emergency shelter, there is loss to the cultural, social and human aspect of a community.

Table 4-8. Pre-disaster community capital score

Occupancy type	Built Capital	Social Capital	Human Capital	Cultural Capital	Political Capital	Financial Capital	Natural Capital
SFD	0.97	0.65	0.24	0.97	-	0.97	-
MFD	0.32	0.32	0.08	0.32	-	0.21	-
Retail	0.55	0.37	0.55	0.33	0.55	0.55	-
Government	0.23	0.23	0.23	0.14	0.23	0.23	-
Commercial	-	-	-	-	-	-	-
Entertainment	-	-	-	-	-	-	-
Storage	-	-	-	-	-	-	-
Religious	-	-	-	-	-	-	-
Civic	-	-	-	-	-	-	-
Recreational	-	-	-	-	-	-	-
Industrial	0.03	0.02	0.01	-	0.01	0.03	-
Education	0.18	0.18	0.18	0.18	0.18	0.12	-
Hospital	0.11	0.11	0.11	-	0.11	0.11	-
Fire station	0.00	0.00	0.00	-	0.00	0.00	-
Utility	-	-	-	-	-	-	-

Table 4-9. Post-disaster community capital score

Occupancy type	Built Capital	Social Capital	Human Capital	Cultural Capital	Political Capital	Financial Capital	Natural Capital
SFD	0.35	0.23	0.09	0.35	-	0.35	-
MFD	0.08	0.08	0.02	0.08	-	0.05	-
Retail	0.05	0.03	0.05	0.03	0.05	0.05	-
Government	0.01	0.01	0.01	0.01	0.01	0.01	-
Commercial	-	-	-	-	-	-	-
Entertainment	-	-	-	-	-	-	-
Storage	-	-	-	-	-	-	-
Religious	-	-	-	-	-	-	-
Civic	-	-	-	-	-	-	-
Recreational	-	-	-	-	-	-	-
Industrial	0.02	0.01	0.01	-	0.01	0.02	-
Education	0.06	0.06	0.06	0.06	0.06	0.04	-
Hospital	0.01	0.01	0.01	-	0.01	0.01	-
Fire station	0.00	0.00	0.00	-	0.00	0.00	-
Utility	-	-	-	-	-	-	-

As shown in Table 4-8 and 4-9, there is a significant difference in measurements for pre-disaster and post-disaster. To represent the community capital loss, the differences in values in Table 4-8 and 4-9 are computed and presented as organizational loss in Table 4-10.

The loss is most significant to political and human capital which may have a detrimental effect on the community.

Table 4-10. Community Capital loss

Type of Capital	Before	After	Organizational Loss	Organizational loss (%)
Built	2.40	0.58	1.83	76%
Social	1.89	0.44	1.44	77%
Human	1.42	0.25	1.17	82%
Cultural	1.95	0.53	1.42	73%
Political	1.09	0.14	0.95	87%
Financial	2.24	0.53	1.70	76%
Natural	-	-	-	-
Total	11.59	2.51	9.08	78%

4.3 Linking community capital measurements

The losses computed in the above sections are combined to get a comprehensive view of organizational losses to the community. Figure 4-2 presents the dashboard of community capital loss in Centerville. Number of damaged building (built capital), dislocation rates (social capital), morbidity rates (human capital), accessibility to resources (political capital) are direct losses to the community. As evident in Figure 4-2, more than 90% of community capital generated through retail, government, hospital and fire station is lost post-disaster. In addition to loss due to critical injury, fatality and PTSD, critical features of human capital through knowledge and skill. Residential buildings, especially SFDs, contributes the highest towards community capital and therefore also suffers more than 50 % loss.

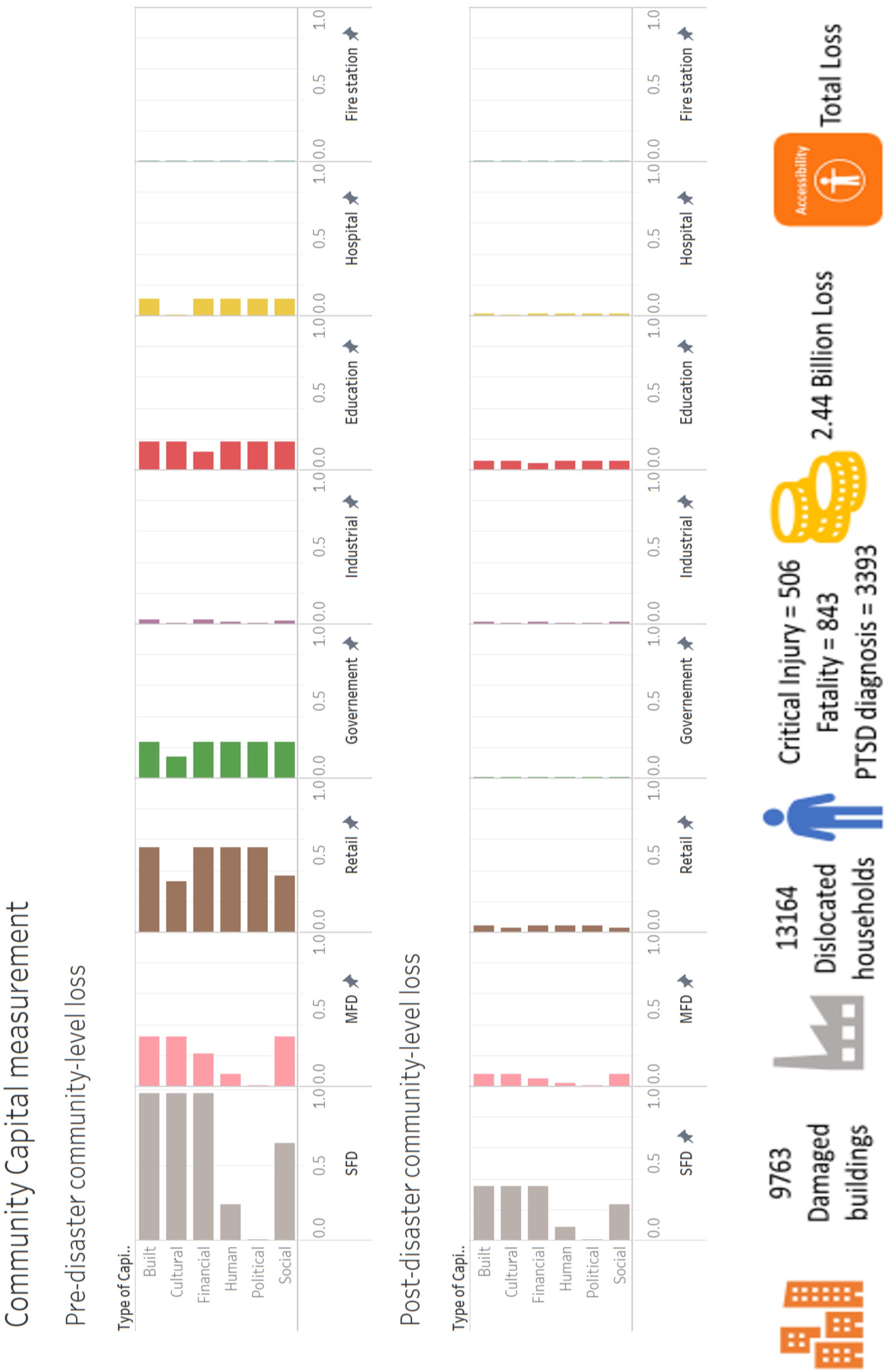

Figure 4-2.Community capital loss in Centerville

The two-tiered approach adopted in this framework evaluates the impact on key factors considered in the definitions of community capital per NIST Community Planning guide [NIST (2016)]. The community-level approach portrays the loss in community functionality that is overlooked in a single-building damage estimation. The results from this approach, once validated, can be used to make design and retrofit prioritizations and other recommendations that suits the community's needs by key factors governing the community capital and building functionality.

Chapter 5: Discussion and Conclusion

The necessity to include community capitals in loss estimation models to improve design and mitigation planning is a topic in disaster research that is actively being investigated. This thesis helps fill a gap in knowledge by proposing a novel approach for quantitative measurement of community capitals using building portfolio and population data at the community-level. A literature review of the seven-community capitals was performed to identify traditional loss measurements associated with each community capital that were within the scope of the study. These included dislocation rates (social capital), morbidity rates (human capital), accessibility changes (political capital), and repair costs (financial capital) aggregated to capture collective loss in a community. A scoring system based on the definitions of community capitals used in the NIST Community Planning Guide [NIST, (2016)] and adopted from Ritchie and Gill (2011). Community capital measurements were executed across the disaster timeline using this scoring system to obtain loss to community functions. A comprehensive view of the impact of the disaster scenario on the community is attained by integrating the results of the scoring system along with traditional building-level loss aggregated at the community-level. The proposed framework was demonstrated on a testbed, Centerville. Not only does this research contribute significantly towards integrating buildings and social characteristics in a loss estimation model for community resilience, it also opens up a new perspective to be further explored and incorporated into decision making on construction and planning for stakeholders, contractors, and government officials at a community-level.

This thesis offers several new contributions to the current state-of knowledge. First, existing community resilience frameworks lacks methods to quantify all community capitals. The scoring system presented here proposed a way to quantify six community capitals using the key factors that define it and thereby assist decision-makers to prioritize infrastructures and organizations based on community capital. Second, this work provides a way to quantify the impact on community capitals following a disaster, which can be used to redistribute resources, rebuild and improve the quality of recovery.

Third, the framework and Centerville example illustrate the role of different occupancies in a community that show a different strength than what might be assumed by the current structure of Risk Category in ASCE- 7. For example, building damage to hospital, although severe, is often considered more detrimental than damage to a residential unit. However, the vast majority of buildings in a community are residential, therefore even though at a building-level residential unit seems to impact fewer people, the collective impact may be much worse than that of a hospital. Factors like social relationships and networks, individuals with irreplaceable skills and knowledge, the unique culture and orientation of the community, loss of access to resources supporting the structure of the community are obstructed.

Furthermore, this study pointed out the impacts on the relationship between the building portfolio and organization throughout a community. The current practice of assigning design level and prioritizing structural design and performance based on risk category adopted in ASCE-7 where residential buildings is categorized as 'Risk category II - structures whose failure does not pose a substantial risk to human life' does not consider the impact on important social dynamics such as human and social capital. In a community, vast majority of the buildings are single-family homes and therefore during a disaster, residential buildings are most affected. Although at building-level only one household maybe affected, at a community-level that number is substantial.

Additionally, the proposed framework, with further research and validation, also provides a way to capture how buildings contribute towards each community capital which may be used to prioritize their design and constructions. For example, when residential buildings are compared with schools, community capitals generated by residential buildings is more than that of schools. Improving the designs for residential buildings, therefore will be beneficial for the community.

The purpose of this work is to aid community decision makers in either mitigation plans or to aid in response and recovery efforts post-disaster. The proposed framework can help communities understand and develop the distribution of community capitals to fit the needs of community members and community-level constraints. This approach can be employed preceding a disaster to have improved designs and better recovery plans or it can be used as part of disaster response to adapt and eliminate downtime as much as possible.

While the proposed framework includes a broad range of factors that play a role in community functionality following a disaster, like any new proposal there are limitations to this study and further research is required. Restrictions on the scope of this study such as exclusion of natural capital in both measurements and cultural capital in building-level loss measurements stemmed from insufficient data and research on the topic. Therefore, as part of future work, factors such as environmental impact and cultural impact on community should be explored and incorporated. Natural capital may be estimated through commercially available software such as ATHENA Impact Estimator for Buildings (2017), and cultural capital could be estimated through identifying functionality of a building that impacts customs and traditions of a society.

Another limitation is that transportation, power and water supply systems were considered outside of the current scope, but their relationship with the community capitals should be investigated in future research. Populace characteristics used centered on fatality rates, injuries and PTSD diagnoses amongst individuals. For a broader study, data on health changes amongst age groups, disabled and institutionalized populace and other characteristics may be included. Additionally, economy in the community is tied to repair cost and assessed building values. This feature can be enhanced to include property value change, income, savings, profit or loss from business, self-retirement plans and more.

Likewise, all the assumptions made in the selection and preference of criteria and adjustment factors in the framework were assigned based on expert opinion. Additional research through field work and/or other investigation procedures, is needed to support adjustment factor and score assignments, and ultimately to justify the model. However, this thesis serves a novel perspective in disaster research and hopefully will aid in a branch of study to investigate a series of research including the influence of building functionality and social institutions on community capitals.

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