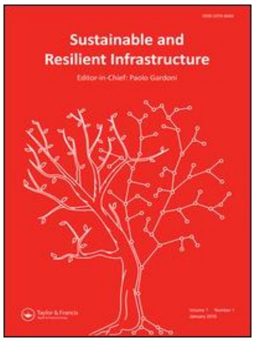

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Defining organizational functionality for evaluation of post-disaster community resilience

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ABSTRACT
Communities are complex systems defined by the interaction of social, economic, environmental, and physical systems. The dynamic response and recovery of a community to a disaster is often tied to the response and recovery of its organizations. This paper employs the Community Capitals framework to understand how organizations contribute to community resilience. The organization-level functionality is defined as the capability of an organization to be used for its intended purposes. Organizations are not solely physical objects, *staff* and *supply chain* are identified as critical non-physical components contributing to organizational functionality alongside conventional physical components. Fault trees and a probabilistic framework are developed to measure organizational functionality failure. A fault tree is presented in detail for three organizations, namely, *banks, gas stations*, and *schools*, to illustrate the different components necessary for functionality of different organizations. Lastly, a framework for evaluation of community resilience based on organizational functionality is proposed.

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Community resilience; organizational functionality; community capitals; fault tree analysis; functional recovery

1. Introduction

As the years of research on community disaster resilience continues, more is understood about what immediate disaster impacts are, how to prevent immediate impacts through mitigation and response, and what services and critical infrastructure need to be prioritized in the immediate aftermath. While long-term recovery has always been articulated as part of the disaster lifecycle, less attention has been spent on understanding how long-term recovery takes place, and what factors or interventions increase or decrease recovery times and change recovery trajectories. This latter statement is true for communities, as well as the long-term recovery of community components, such as businesses, schools, housing, and households (Sutley & Hamideh, 2020). In addition to causing casualties and damage to physical infrastructure, disasters disrupt the availability of social services critical for a community's long-term recovery. As a result, different dimensions of community resilience (e.g., population, ecosystem, government services, etc.) are affected (Cimellaro et al., 2016).

Historically, building codes consider occupancy of the building during the design process but do not consider how the building is otherwise part of a larger system, i.e., a community. The building code design goals, for most buildings, are to provide functionality during routine events and to maintain occupant safety during disasters; the exception is for nuclear facilities and a small group of emergency buildings (e.g., hospitals, police stations, fire stations, etc.) that are considered vital during and after disasters. The significant decrease in the number of collapsed buildings and casualties caused by recent disasters, relative to other countries, proves that code-based designs have been largely successful in meeting their design objectives. For example, no shaking-related fatalities were reported during the July 4th and 5th, 2019 Ridgecrest California M 6.4 and M 7.1 earthquakes. Similarly, apart from very vulnerable building types, such as unreinforced masonry structures, very little structural damage was observed in San Bernardino County and the city of Ridgecrest, the most heavily impacted areas. However, nonstructural damage and discontinued services continue to be prevalent after disasters and very costly, causing an estimated $1 billion in losses after the 2019 earthquake (Osalam, 2019).

This continued disruption and billions of dollars in losses every year by disasters are not representative of resilience. To move towards resilience, next-generation building codes should extend their design goals to

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incorporate functionality goals into the design process (McAllister, 2016), where functionality goals must include more than the physical aspects of infrastructure. Designing with functionality goals in mind does not necessarily mean a significant increase in construction costs. Applying the FEMA P-58 methodology, Haselton et al. (2018) demonstrated that it is possible to design new buildings with considerably improved performance and a significant drop in repair cost and time with very small additional initial investment. Even still, research is needed to understand how to incorporate functionality goals into codes and standards, including understanding which buildings should be prioritized. The present work begins to chip away at this latter need by examining how different organizations contribute to community resilience, and how to model functionality and functionality loss of organizations. Organizations create an important extension, given that it is the people who work and utilize buildings and infrastructure that will enable higher level resilience goals to be achieved, including innovation, adaptability, and transformation. This work distinguishes organizations from social institutions and businesses, although there is overlap, and both have been the focus of other research. *Social institutions* integrate the norms and values of a community to meet its members' social needs such as education, family, healthcare, and religion. However, they do not encapsulate other necessary products and services, offered by organizations such as grocery stores, needed for communities to function and recover after a disaster. The term *businesses* focuses on the commerce aspect of organizations, as opposed to the product or service offered, and how said service supports a community beyond economics. Thus, here we define organizations as any entity that is designed to provide products and services to a community in an effort to meet the community members' needs from various perspectives.

Over the past decade, several community resilience studies have begun to develop conceptual models of resilience in terms of functionality and assess the impacts of the functional built environment on community recovery following disasters. Lin and Wang (2017) developed a stochastic functionality restoration model for the physical recovery processes of buildings. The model predicts post-disaster functionality recovery time and trajectory for a community's building portfolio using two metrics: (1) the portfolio recovery index and (2) the portfolio recovery time. Cimellaro et al. (2010) developed a building-centric framework to quantitively evaluate the resilience of healthcare facilities subjected to earthquakes. The evaluation was based on the dimensionless analytical functions associated with variation in post-disaster functionality of system during the recovery period. Nevill and Lombardo (2020) distinguished structural functionality (defined as the ability to safely provide shelter) from total functionality of a building (which includes the functionality of nonstructural components, such as electric power, water, and transportation access), and proposed a scale to measure structural functionality of light-framed wood buildings. The scale was presented through: (1) a set of structural functionality indicators for windstorm damage, and (2) a set of guidelines to extend the indicators to other hazards. Burton et al. (2016) presented a framework for incorporating probabilistic building performance limit states in the assessment of community resilience to earthquakes. They proposed building-level recovery functions considering uncertainties in the recovery path to a limit state and employed a probabilistic approach to evaluate functionality restoration for buildings. The application of the proposed procedure to model post-earthquake community-level recovery functions was demonstrated using a case study. Davis (2013, 2014) illustrated the relationship between community resilience and post-earthquake functionality of water systems using a case study of the Los Angeles Water System. After making a clear distinction between functionality and operability of water systems, the work demonstrated how functional water systems that are able to provide post-earthquake services to other lifelines and emergency operations, help to improve community resilience.

The previously reviewed works adopted an infrastructure-centric (mostly buildings) definition for functionality and neglected the effects of non-physical components. However, there are a few studies that have recognized the role of buildings in supporting society and offered more holistic functionality models for community resilience assessment. For example, by assessment of the observational data on the performance of the hospitals in past earthquakes, Yavari et al. (2010) traced four interacting components (structural, non-structural, lifelines, and personnel) influencing a hospital's functionality and used them to develop a predictive model of hospital functionality in the event of an earthquake. Later, Jacques et al. (2014) studied the functionality of the Canterbury healthcare system after the 2011 Christchurch earthquake. Adopting a multidisciplinary approach, Jacques et al. (2014) identified that the functionality of crucial hospital services primarily depends on the availability of three factors: *structure, staff*, and *stuff*.

Then, Mieler and Mitrani-Reiser (2018) performed a comprehensive review of the state of the art in assessing earthquake-induced loss of functionality in buildings. The review commented on how functionality loss within individual buildings and infrastructure can affect a community at different spatio-temporal levels. After identifying incidents that commonly cause loss of functionality in a building, a fault tree model was applied to capture and relate these incidents to the building's functionality. Then, to demonstrate how the availability of such incidents affects post-earthquake building functionality recovery, the conceptual functionality-restoration curves were presented. It is concluded that existing analytical models for assessing loss of building functionality need to be refined to include all components that contribute to functionality, including non-physical components like staff availability. Finally, Choi et al. (2019) moved beyond healthcare systems and introduced an interdisciplinary platform for planning community post-disaster recovery within the framework of seven layers of critical infrastructures (i.e. civil, civic, financial, environmental, educational, and cyber). The framework articulates interdependencies within and between functional physical infrastructure and structure-based systems (civil layer), and the other layers that are important to sustain the functionality of a community during post-disaster recovery.

Collectively, these studies provide a strong foundation necessary for advancing the state of knowledge on the concept of functional recovery for communities and their components. This paper advances these lines of inquiry by introducing and defining the concept of organizational functionality as it relates to community resilience. A conceptual framework for linking organizations to community functionality is proposed using the Community Capitals framework. The paper closes with a probabilistic approach to evaluate organizational functionality failure used to guide the development of a procedure for the practical assessment of a community's disaster resilience.

2. The Role of Organizations in Community Resilience

A community is a complex system of systems comprised of dynamically interacting non-homogeneous built, natural, and human infrastructure (Bozza et al., 2015). Resilience is also a multidimensional concept, particularly when applied at the community level; community resilience cuts across different stressors (natural, man-made, biological), scales (state, regional, local), and community dimensions (physical, natural, social, financial, political) (Koliou et al., 2018). Community disaster resilience is measured based on a community's ability to prepare and mitigate a hazard (natural and/or human-caused), respond dynamically to reduce consequences of any functionality loss when disasters do occur, and carry out recovery actions that minimize recovery time and future vulnerabilities in an equitable manner (Council, N. R, 2012; DHS., 2008; House, 2013; Nations, 2011; SDR., 2005). Preventing functionality loss is the first part of assessing resilience, where functionality represents how well a system operates to deliver its products or meets its intended purposes (Mieler & Mitrani-Reiser, 2018). Functionality, including community functionality, building functionality, and organizational functionality, varies across the disaster timeline. Figure 1, inspired from the NIST Community Resilience Planning Guide (CRPG) (NIST., 2016), illustrates the temporal variability of functionality following a disruptive event.

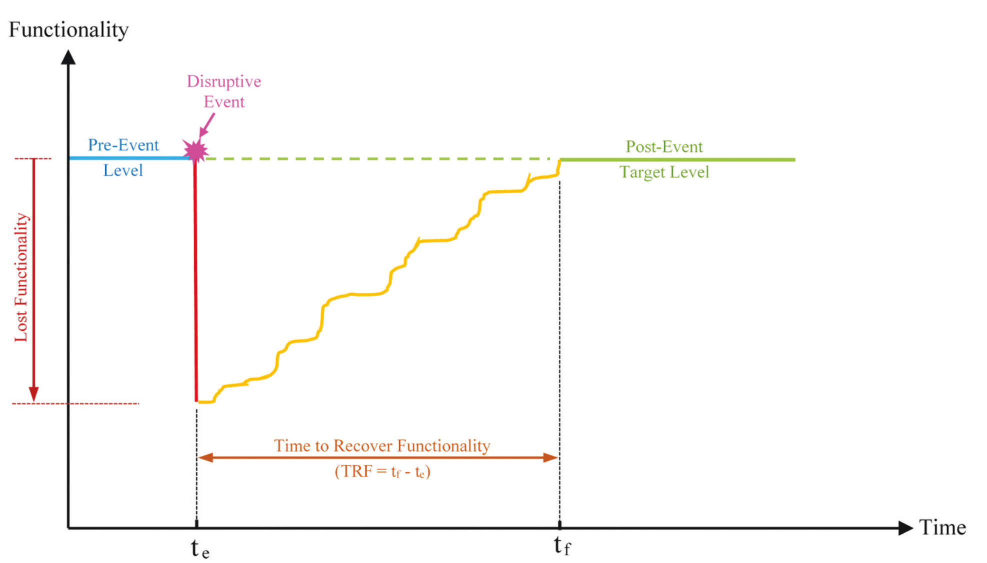

Figure 1. Resilience definition in terms of functionality and the time to recover functionality.

The period between the time of the disruptive event (t_e) and the time of target functionality restoration (t_f) is defined as the Time to Recover Functionality (TRF). TRF is a measure of how long it takes before a system becomes functional after a disruption. In Figure 1, the pre-event functionality is normalized for deterioration or improvement effects during normal operation and the post-event target level is set as the pre-event level. However, true resilience must also incorporate building back better such that pre-event vulnerabilities are not re-established during recovery. This is referred to as service equilibrium shift by Davis (2014), and is outside of the scope for this paper.

The dynamic response and recovery of a community to a disaster is directly tied to the response and recovery of its organizations. Past research has illustrated the undeniable connection between community resilience and the functionality of its organizations (Dalziell & McManus, 2004; Lee et al., 2013); thus, understanding and modeling such relationships will provide critical insight into a community's resilience. Therefore, in line with the community definition, in seeking resilience, a community's primary objectives should be minimizing (1) the amount of lost functionality after a disruptive event, and (2) critical organizations' TRF to an acceptable level. Here, two important metrics are introduced towards these objectives: (1) the Minimum Acceptable Level of Functionality (MALF) which limits the value of lost functionality and provides a lower threshold for the system's post-event target functionality; and (2) the Maximum Tolerable Period of Disruption (MTPD) which represents the maximum allowable time that a system can be non-functional before its impact is deemed unacceptable. These metrics are revisited later for the evaluation of organizational functionality failure.

2.1. Organizations and the Community Capitals Framework

To better articulate different capacities and components in a community, social scientists have developed the Community Capitals (CC) Framework (Flora et al., 2005). The CC framework assesses the stock of seven capitals, the types of capital that are invested in a community, and the interaction of these capitals (Emery & Flora, 2006). Ultimately, these seven capitals, or community assets, interact and build upon one another at different spatio-temporal scales, creating and enhancing a collective (community) response toward disruptions. A community's functionality is defined by its stock of the following assets

Natural capital, or assets tied to the location: weather, wildlife, natural resources, and beauty; quality of air, land, water, level of biodiversity, and scenery are all examples (Emery & Flora, 2006; Flora, 2015).

Cultural capital, or the traditions, language, and social creativity that emerge in an area. This can include inherent social values, the way attitudes are nurtured, and what heritage is recognized and celebrated in a community (Flora, 2015; Mattos, 2015).

Human capital, or the skills and abilities of people in a given area, which contributes to community building, knowledge sharing, and innovation. This can include educational attainment, technical skills, health and vitality, creativity, and diversity of the population (Flora, 2015). Human capital relates to leadership's ability to focus on assets, be proactive to the future, and access outside resources to improve practices (Mattos, 2015).

Social capital, or the network connections amongst people that 1) build cohesion through bonding; 2) bridge together loose social ties; and 3) link community members to those in power. This can be measured through network structures, group membership, common goals, diversity, and trust in a community (Flora, 2015).

Political capital, or the access to resources and officials in order to influence standards and rules. The level to which a community organizes to interact with the government or leverage a collective voice is an important metric of this capital (Flora, 2015; Mattos, 2015).

Financial capital, or the resources to spur community development through business, civic, and social entrepreneurship (Mattos, 2015). This can include state and federal tax monies, investments, loans, grants, and poverty rates (Flora, 2015).

Built capital, or the infrastructure that supports many aforementioned activities, often becoming a focus of community development. This can include housing stock, transportation infrastructure, telecommunications, utilities, and hardware (Flora, 2015).

All seven capitals are essential and their details are distinctive to each specific community; however, here it is proposed that built capital has a unique role in supporting the other six capitals. Different components of the built capital work together to enable organizations through a complex network of interacting capitals. An overview of this concept is illustrated in Figure 2. Disaster resilience is often studied as infrastructure resilience, where multi-layer network models connect the various physical infrastructure systems (lifelines). To study community resilience, the analysis must extend beyond physical infrastructure systems to social,

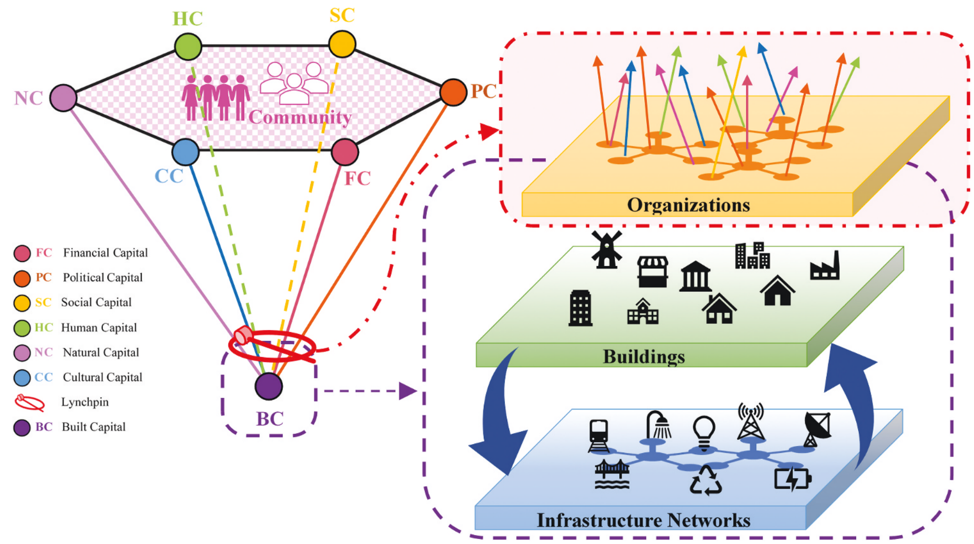

Figure 2. Dissecting the Community Capitals in terms of Community Functionality.

economic, and environmental dimensions. Relating the seven community capitals to organizations enables this extension.

Organizations inherently rely on the built capital through either the building they occupy or the benefit they derive from infrastructure networks; organizations also contribute to a community's human, social, political, financial, natural, and cultural capitals through their services, users (including consumers and employees), and supply chains. Hence, as illustrated in Figure 2, organizations are the lynchpin connecting the built capital to the other capitals. Multi-colored arrows projecting out of the organization layer in Figure 2 depict how organizations (generally) support one or more of the community capitals, where the colors of the arrows correspond to the various capitals. Large arrows on the right capture the well-established dependencies within the built capital, specifically between buildings and infrastructure network layers.

As discussed in (Daniel, 2019), oftentimes community capitals will overlap. For example, communities with greater social and human capitals tend to have more intentional resilience planning whereby stakeholders unite around common goals and risks with a sense of trust, they share ideas which can drive innovation and increase resilience (National Academies of Sciences, E., & Medicine, 2019). Different organizations can mobilize community capitals, particularly human and social capitals (Choi et al., 2019). For example, after Hurricane Katrina, the Mary Queen of Vietnam Catholic Church used its members' social networks to relay critical developing information during the disaster (human and cultural capital), provide shelter for those who could not evacuate (built capital), and build community morale and structure in recovery (financial, political, and human capital). In this case, a faith-based organization filled critical gaps in community recovery and contributed to the Versailles Parish coming back quickly and more robustly than nearly all of its neighboring parishes (Aldrich, 2012; Rivera & Nickels, 2014).

Organizations play an important role in community resilience before, during, and after the recovery phase. Community resilience requires a certain type and number of organizations to maintain a minimum acceptable level of functionality after disruptive events. Communities need to ensure that their organizations can be recovered within a specified period to support their short, intermediate, and long-term recovery goals. The manner in which organizations contribute to a community's cultural character, built environment, social and human ability, and economic engine is complicated. A wealth of services are offered through organizations in a community, from basic goods such as clean water and food, to specialized services, such as healthcare and education. Each service creates a small, critical link to community functionality through its connection to the community capitals, creating an interdependency between community and organization, and from organization to organization. Consequently, the functionality of the buildings these organizations occupy, as well as their inner organizational constraints, requires further investigation. For organizations to fully contribute to community functionality and resilience during a disaster, resilience scholars and planners must understand the inner mechanisms of how organizations function. This paper connects these internal organizational components in order to analyze the functionality of organizations.

2.2. Defining Organizational Functionality

This paper proposes the following definition of organizational functionality; *organizational functionality is the quality in performance of an organization and its ability to be used for its intended purposes*. Organizations provide various products for the community. Here, a product is any good or service, either tangible or intangible, that can be offered by an organization to satisfy a want or need. *Primary products* are the main objective and intended purpose of an organization; any other offered product(s) are denoted as *secondary products*. For example, a gas station is a facility that sells fuel and lubricants for motor vehicles (primary products). However, many gas stations have convenience stores or tunnel carwash (secondary products). To characterize organizational functionality, it is necessary to understand the type, quality, and quantity of primary and secondary products provided under normal operations, to then define organizational functionality states. Organizational functionality states are used for step-wise modeling of functional recovery trajectories. Here, considering several similar studies available in the literature on building functionality (Burton et al., 2016; Cimellaro et al., 2010; C. A. Davis, 2019; Lin & Wang, 2017; McDaniels et al., 2008; Mieler & Mitrani-Reiser, 2018; Nevill & Lombardo, 2020; NIST., 2016), five discrete functionality states for an organization are defined:

Out of Service Organization: Either internal or both internal and external essential components of organizational functionality are disrupted; consequently, the organization is NOT working.

Intrinsically Operable Organization: The essential internal components of organizational functionality are maintained, or restored; however, the organization is NOT working yet since at least one essential external component of organizational functionality has not been recovered.

Fully Operable Organization: Both internal and external essential components of organizational functionality are maintained, or restored so that the organization is working but NOT at an admissible level; some or more secondary products may be completely interrupted, however, primary products are available albeit at an *unacceptable* capacity or quality, or in an unsustainable fashion.

MALF Organization: The organization is working at an admissible level of functionality; some or more secondary products may be completely interrupted, but primary products are available albeit at an *acceptable* reduced capacity and quality, and potentially in an unsustainable fashion.

Fully Functional Organization: The organization is working properly and providing all primary and secondary products at the intended level of quality and quantity in a sustainable fashion.

Figure 3 transforms the functional recovery trajectory of an organization into an equivalent step function using the defined post-disaster functionality states. The percent of functionality is 100% for the Fully Functional state, measured relative to the pre-event level, and 0% for Out of Service State. The percent of

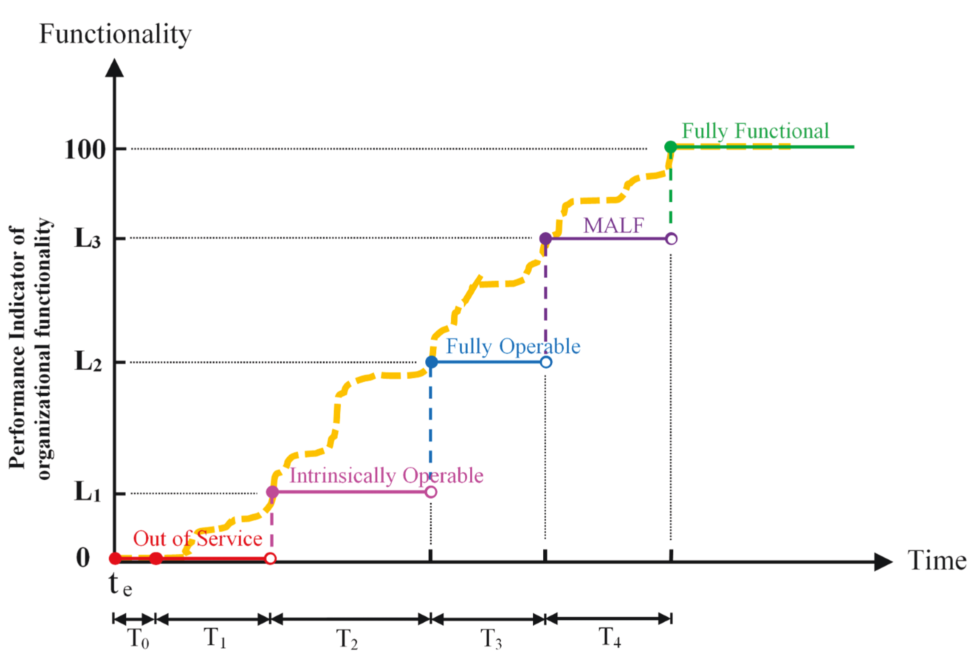

Figure 3. Post-disaster functionality states of an organization.

functionality associated with Intrinsically Operable (L_1), Fully Operable (L_2), and MALF (L_3) states are organization-specific and can be determined empirically, through engineering judgment, or through input from the owner or manager of the organization being analyzed. However, a systematic approach to estimating the L_1 is proposed later in this paper. The key concept for the MALF state is that the admissible intended functions of an organization are often something less than a Fully Functional state. Various reasons can cause the MALF state; for example, using a temporary power supply instead of a permanent one in a hospital (e.g. a back-up generator being used because electricity is out) may increase the waiting time to receive a particular health-care service but the service is available at a reduced capacity. The organization will work at the MALF state if the available reduced capacity is equal or greater than the admissible capacity, otherwise, the available capacity will be ignored and the organization will be considered at the Fully Operable state.

As shown in Figure 3, when a disruptive event occurs, an organization's functionality shifts to the Out of Service State for a period T_0. Similar to the time lapses for mobilizing resources and decision-making discussed in previous works (Comerio, 2006; Comerio & Blecher, 2010), T_0 represents a delay time that accounts for the amount of time where that organization must contact employees, survey and assess physical assets, such as the building, equipment, and inventory, and perform any other assessments before the organization can potentially move into a functionality state. T_1, T_2, T_3, and T_4 denote the time spent in the Out of Service, Intrinsically Operable, Fully Operable, and MALF states, respectively. The TRF is the sum of the time spent in each state previous to the MALF state, including T_0.

Although the organizational functionality states are shown sequentially in Figure 3, the organization can move directly into any of the other states after time T_0. Furthermore, since the Intrinsically Operable state is based on the outage of an external component, it and the Fully Operable state do not necessarily happen successively, although they can.

Organizational functionality can be related to a community's functionality through the networked relationship shown in Figure 4. Applying fundamental concepts from Graph Theory (Trudeau, 1993) to visualize the bi-directional relationship, wherein a node represents (a) a community, (b) an organization, (c) a building, or (d) an infrastructure network. The relationships between nodes are represented by edges, which can manifest as their communication, interaction, or supply chain connections (Li et al., 2019). Each infrastructure (blue) node (built capital, e.g., water network) is a set of interconnected components (e.g., storage tanks, pipe networks, valves, pumps, etc.) that work together to provide a service to the organizations (red nodes). Organization nodes interact to support the functionality of the community (green) nodes. Each community node consists of sub-clusters of the other six community capitals, as shown on the right side of Figure 4. Thus, as shown by the red-dashed outline marked (a), organizations are supported by infrastructure services, and as shown by the green-dashed outline marked (b), communities are supported by organizations.

The following section describes the relationships, dependencies, and other internal components that cause organizational functionality loss in a quantitative framework.

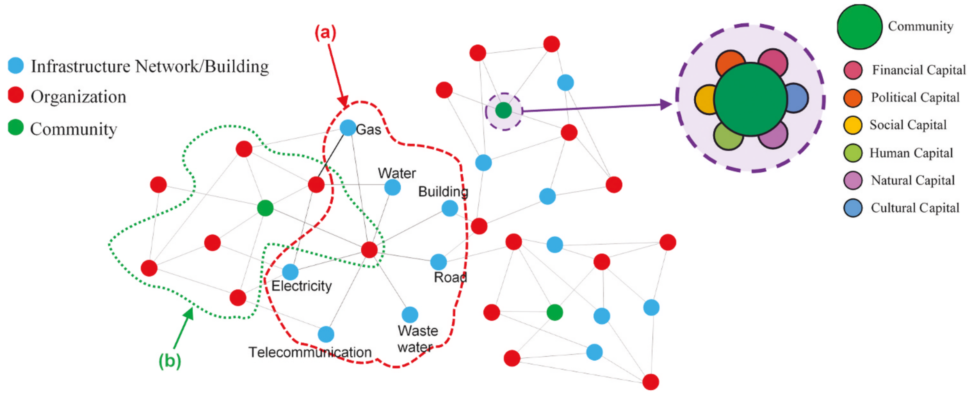

Figure 4. Relating organizations to the community capitals: a) organizations are supported by infrastructure services (built capital), b) communities are supported by organizations.

3. Measuring Organizational Functionality

3.1. Defining Failure through Fault Tree Analysis

Fault tree analysis (FTA) is a simple analytical technique that has been widely used for quantitative reliability and safety analysis. FTA can be used for any system which is composed of discrete components with independent probabilities of failure. The fault tree (FT) itself is a qualitative and graphical model that combines a series of parallel and sequential failure events which will lead to the occurrence of a predefined undesired event in the system. This predefined undesired event is the top event of the FT. A FT applies logic gates to combine the basic events and connect them to intermediate events that lead to the top event (Ruijters & Stoelinga, 2015; Vesely et al., 1981). FTA is executed using two primary techniques: (1) qualitative vulnerability detection through a logical expression of the top event in terms of the basic events; (2) quantitative measurement of the probability of occurrence of the top event obtained through combining the failure probabilities of the basic events (Durga Rao et al., 2009).

In a quantitative FTA, logic gates, more specifically AND gates and OR gates, combine the probabilities of connected events using basic probability rules. In engineering risk assessment using FTA, the combined failure probability of a system (S) which consists of n components (s_1, s_2, ..., s_n) that are connected with AND and OR gates, can be calculated as (Porter & Ramer, 2012):

$$P(S\,|AND) = \prod_{i=1}^{n} P(s_i) \tag{1}$$

$$P(S\,|OR) = 1 - \prod_{i=1}^{n} [1 - P(s_i)] \tag{2}$$

where $P(S)$ is the failure probability of the system, $P(s_i)$ is the failure probability of the ith component connected to that gate, and Π denotes the product. The AND gate represents a parallel system in which a system will not fail unless all of its components fail, whereas the OR gate depicts a system in series in which the failure of any component leads to system failure.

3.2. Causes of Organizational Functionality Loss

Disasters, small and large, can damage buildings, cause lifeline service outages, disrupt supply chains, and displace people (employees and customers), all leading to organizational functionality loss. If the amount of the loss exceeds the predefined lower threshold (the MALF) and organizational functionality does not restore to the MALF before the MTDP, the organizational functionality will fail. Then, the availability of an organization's primary products is a key factor in modeling the organizational functionality failure. Building off of the work

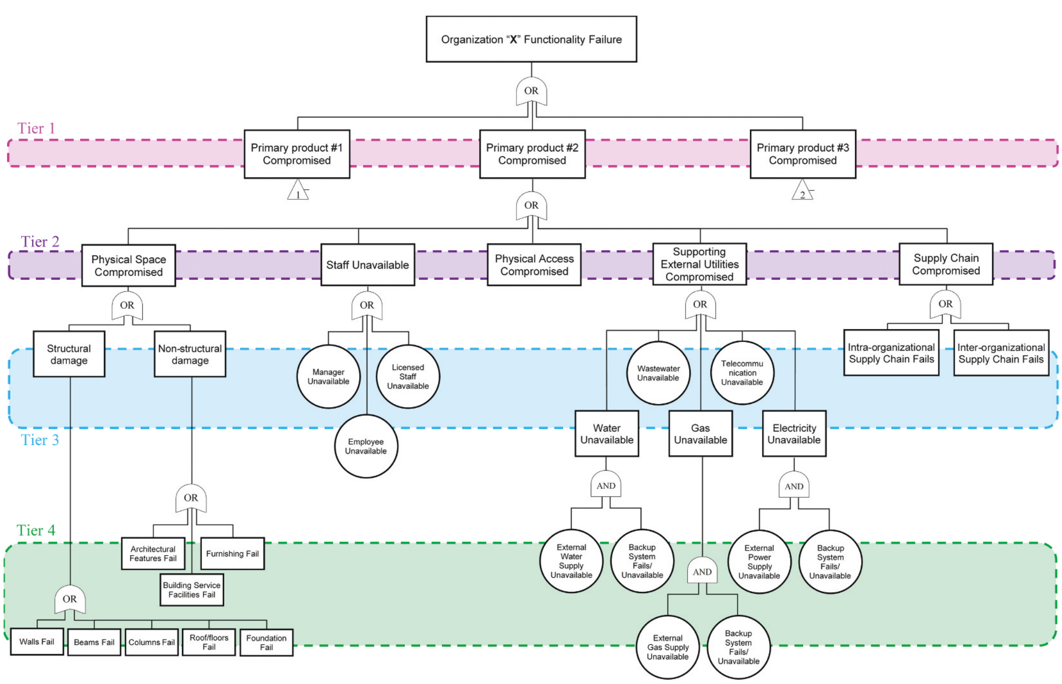

Figure 5. Fault tree for displaying the incidents that commonly cause organizational functionality loss in a hypothetical organization with three primary products.

by Yavari et al. (2010) and Jacques et al. (2014) on healthcare facilities, Figure 5 presents a generic fault tree for organizations, setting organization functionally failure as the top event. Beneath the top event is the first tier of intermediate events: the organization's primary products being compromised, where three primary products are arbitrarily shown in Figure 5 and the tree is developed for the second product as an example. The Tier 1 events are connected to the top event through an OR gate, meaning that if any Tier 1 event occurs, the organization will lose some of its functionality. Tier 2 consists of five intermediate events that are similarly connected to the Tier 1 event through an OR gate, including physical space compromised, staff unavailable, physical access compromised, supporting external utilities compromised, and supply chain compromised. Tiers 3 and 4 further break down failure events into greater detail, where more tiers are possible but cannot be generalized; further detailed failure events will require input from the specific organization being modeled. The structure of the FT in Figure 5 is such that the occurrence of any of the events (basic or intermediate) in the first three tiers will cause some functionality loss and may lead to the top event, showing the wide range of events contributing to organizational functionality. Each event is associated with different recovery costs, recovery times, and consequences which lead to different values of TRF for the organization.

As shown in Figure 5, damage to both structural and non-structural components of a building can endanger the functionality of the organization; main non-structural components that may be available in organizations are classified into (1) architectural features (such as doors, windows, stairs, ceilings, partitions, etc.), (2) building service facilities (including HVAC, lighting systems, fire detection and suppression systems, elevators, etc.), and (3) furnishing equipment (e.g., shelving, desks, furniture, computer stuff, etc.). Even if the building is structurally sound, disruption to physical accessibility may also threaten the organization's functionality. The disruption can be due to temporary road closures, restricted site access, or the destruction of an adjacent building. If employees and customers cannot access the organization, then it cannot function as intended. Sometimes, rather than physical access, access through a loss of telecommunication network can cause functionality loss. Other lifeline service disruptions can similarly cause failure in organizational functionality. For example, restaurants cannot operate without a clean water supply. In general, damage to external lifeline systems, including water and wastewater, energy, and telecommunication, can cause organizational functionality loss.

Adapting the concept of defining rational and irrational components of downtime for buildings (Comerio, 2006) to this study, causes of organizational functionality loss are comprised of both rational and irrational situation-specific components. Substantial research has produced reliable measures of rational components, such as physical space, access, and external utilities being compromised; whereas less research has been spent quantifying the probability of occurrence and recovery times for irrational components. Measuring irrational component failures is complicated and highly variable given the dependence on social, political, and financial factors (Krawinkler & Miranda, 2004). The FT in Figure 5 highlights the irrational components associated with the functionality of an organization, including staff and supply chains. Failure of irrational components will result in some organizational functionality loss even if the rational components are functioning. For example, the COVID-19 pandemic has shown how many organizations can operate remotely without their traditional physical space, as long as their staff and telecommunication services are available. This example also showcases how it is ultimately the people (staff, suppliers, users) who differentiate an organization from a building, and the people who enable higher levels of resilience to be achieved, including innovations, adaptability, and transformation, like moving traditional in-person services to online. The required staff is organization-specific and may include managers, licensed or key personnel, and other employees. Supply chain disruptions are another type of irrational component which can occur in inter- or intra-organizational supply chain, or both. Inter-organizational supply chains are external or between two or more different organizations, such as the relationship between a grocery store and food supplier. Intra-organizational is within an organization and refers to any process within the organization, such as e-mail that connects different branches of the organization. While modeling irrational components is important for understanding and predicting organizational functionality loss, doing such complicates the modeling process, particularly given data limitations.

Furthermore, components contributing to organizational functionality can be classified as internal and external essential components. In the FT in Figure 5, physical space-related events are internal essential components; any other events including those related to physical access, staff, supporting utilities, and supply chain are external essential components. The ratio of the number of internal components to the total number of components on Tier 2 of an organization-specific FT (1:5 for generic FT in Figure 5) can be used as a rough estimate of the organizational functionality percentage associated with the Intrinsically Operable state (L_1) in Figure 3.

3.3. Quantifying Organizational Functionality Failure

This section provides a formulation for quantifying organizational functionality failure using FTA. Looking back to Figure 3, the probability of organizational functionality failure can be interpreted as the probability that the TRF exceeds the MTPD (*P [TRF>MTPD]*), where the value of the MTDP for each organization may be determined using predefined quantities (e.g., NITS CRPG (NIST., 2016)), modeling tools (e.g., Critical Path Method (Lavelle et al., 2020)), and/or through input from the organization owner/manager.

To estimate the probability of organizational functionality failure, (1) the probability of occurrence for each basic event must be known, and (2) the combination of all basic events must be estimated. The latter is done using Equations (1) and (2) based on the logic gates connecting each basic event across tiers. The former is estimated as $P(e,t)$, the probability of the basic component being in the non-functional state at time t subject to a demand parameter e. $P(e,t)$ must be based on disruption levels for each component, which classify component disruption into increments. For rational components, such as structural damage, disruption levels are the same as conventional damage states (e.g., none, slight, moderate, extensive, and complete (HAZUS-MH., 2003)). Damage states are widely used by researchers in the development of fragility functions with criticality that their definitions are quantitative and not subjective. However, for irrational components, as well as for some non-structural components such as building service facilities and equipment, a consensus formal definition of disruption levels does not currently exist in the literature and requires further research.

As such, $P(e,t)$ is determined based on (1) $G(e)$, the probability of that component, subject to demand parameter e, being disrupted, and (2) $\acute{R}(t)$, the probability of the disrupted component being unrestored before time t. Since the component's disruption and restoration time are statistically dependent through disruption levels, the failure probability of the ith component in a FT model with n basic events can be estimated using

$$P^{(i)}(e,t) = 1 - \prod_{DL=1}^{n_{DL}} \left[1 - \left(G_{DL}^{(i)}(e)\right)\left(_{DL}^{(i)}(t)\right)\right] \quad (3)$$

where $P^{(i)}(e,t)$ is the probability of component i being in a non-functional state before time t subject to demand parameter e, Π denotes the product, DL represents disruption levels (assuming n levels of disruption for the component, n_{DL}), and $G_{DL}(e)$ and $\acute{R}_{DL}(t)$ are cumulative probabilities of disruption and restoration time, respectively, for a given disruption level. For rational components, $G(e)$ and $\acute{R}(t)$ can be specified using existing (or new) fragility and restoration functions (Prabhu et al., 2020). However, functions for irrational components cannot (or should not) be modeled using similar fragility functions due to their more complex nature with dependencies extending externally.

Once the probability of occurrence of each basic event is estimated, a Monte Carlo simulation can be applied to determine the probability of occurrence of the FT top event, $F^{(top)}(t,e)$ for a range of values of e and t. $F^{(top)}(t,e)$ gives the probability that the organizational functionality is not recovered before time t subjected to demand e. Employing probability theory and setting t equal to MTPD, the failure probability of organizational functionality and the expected value of the TRF (mean TRF) for a given demand e, can be predicted as

$$P(TRF > MTPD|e) = F^{(top)}(MTPD,\ e) \quad (4)$$

$$Q(t,e) = P(TRF \leq t|e) = 1 - F^{(top)}(t,\ e) \quad (5)$$

$$E(TRF|e) = \int_0^{\infty} t \cdot q(t|e)\,dt \quad (6)$$

where $P(TRF>MTPD|e)$ is the probability of organizational functionality failure, and $E(TRF|e)$ is the organization's mean TRF, given the demand e. $Q(t,e)$ is the cumulative distribution function for the probability of non-exceedance of the TRF, and $q(t|e)$ is its associated probability density function which provides the probability that the organization is functional at time t for demand e. Figure 6 shows a conceptual illustration of $Q(t,e)$ and the organization's mean TRF for a range of hypothetical demand values sorted in ascending order by the intensity/magnitude value ($e_1, e_2, \ldots, e_n$).

The curves in Figure 6a illustrate the time required to restore organizational functionality to the MALF (horizontal axis), and the probability that the TRF takes a value less than or equal to that time (vertical axis). For instance, the probability that the organization's TRF is less than or equal to t_c for demand e_1 is 1.0, which means there is a 100% chance the organizational functionality restores to the MALF before this time.

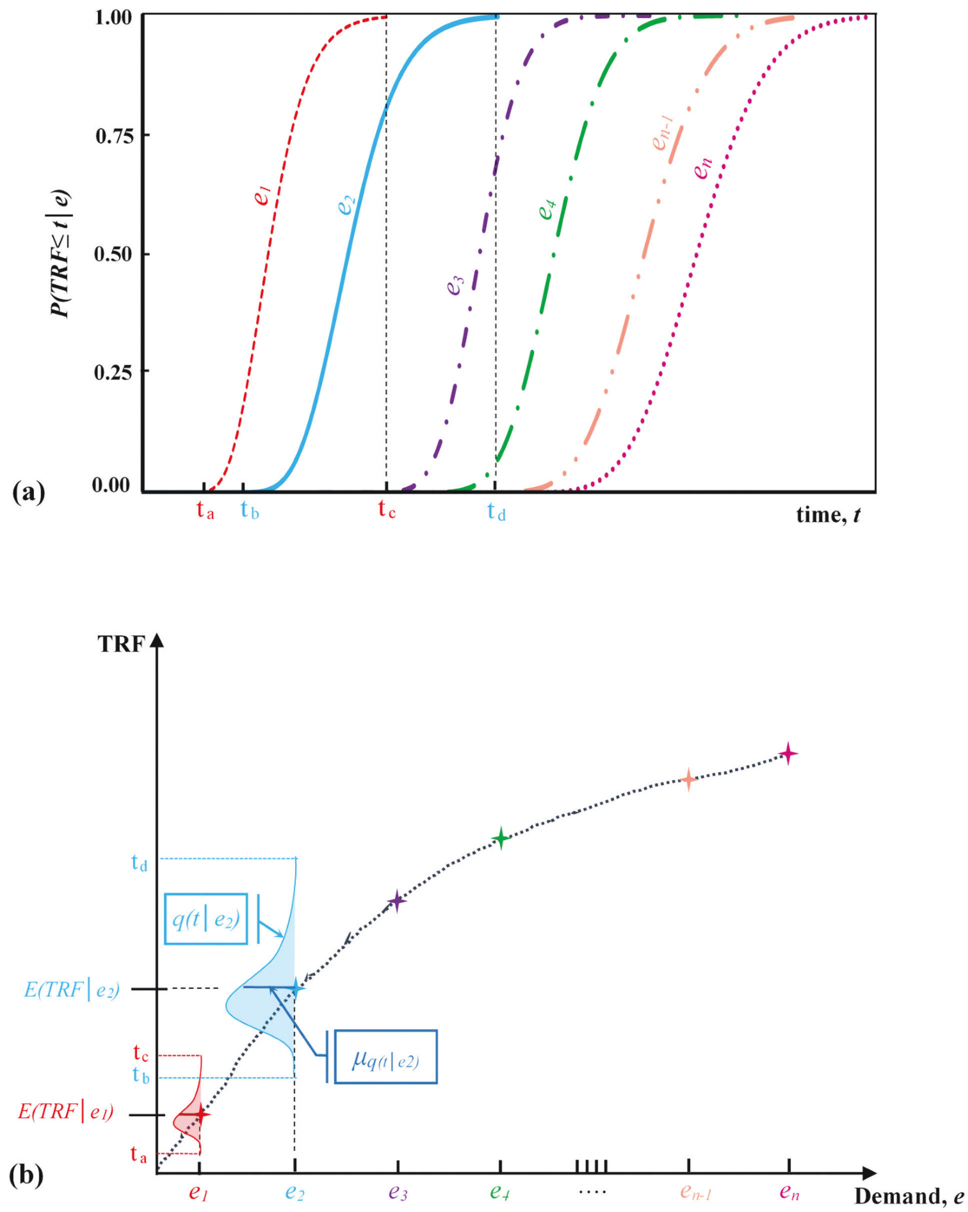

Figure 6. Conceptual illustration of: a) cumulative distribution function for probability of non-exceedance of TRF, Q(t,e); b) organization's mean TRF for a range of hypothetical demand intensity.

Figure 6b fits a curve to values calculated using Equation (6) with varying demand (e_1, e_2, ..., e_n) to illustrate the mean TRF. The colors and symbols in Figure 6a correspond to the same scenarios in Figure 6b.

The main goal of defining organizational functionality, modeling, and quantification of its failure probability in this paper, is to develop a framework for the assessment of a community's post-disaster resilience objectives through measuring the stock of community capitals. The purpose of this framework is to help community decision-makers to develop more informed disaster risk mitigation and long-term recovery plans. In the next sections, to clarify the framework previously formulated, first, fault tree models of organizational functionality for three specific organizations: *banks*, *gas stations*, and *schools* are developed and discussed. Then, a step-by-step procedure for evaluating community resilience using this concept is presented.

4. Application of the Proposed Fault Tree Model for Various Organizations

Although generalized in Figure 5, physical space, access, staff, supporting services, and supply chain differ significantly across organizations. These details must be known in order to prioritize components and begin to understand what is necessary for the minimum acceptable level of functionality (MALF) for a given organization. The application of the generalized fault tree in Figure 5 will differ amongst organization types, and even within a type, depending on size, structure, resource dependencies, and other larger contextual variables. Influential variables are extensive, so this tool must be used in conjunction with accurate data, relevant stakeholders, and simulations, where possible, for an organization (Jacques et al., 2014). Still, the proposed generic fault tree can be adapted to pinpoint vulnerabilities for a given organization, as is done here. To describe key differences across different types of organizations, this section develops fault trees for three specific organizations: *banks, gas stations*, and *schools*, where a specific model for healthcare facilities can be found in (Jacques et al., 2014). The three organizations are selected here based on their different organizational structures, functionality dependencies, and product diversity with respect to each other; they also contribute differently to the community capitals. These organizations do not reach the highest risk category under the current approaches in ASCE7-16; thus, they are not required to be functional following a design-level hazard event though research has shown all three are important for maintaining and restoring community's functionality after a disruptive event (NIST., 2016). Banks, or financial institutions, primarily contribute to financial and social capitals and are less dependent on the physical space they occupy compared to their staff and supply chains. Gas stations, on the other hand, depend on their physical space, access, and supply chain more than their staff. Schools primarily generate social and human capitals, can substantially change their product during a disaster, and overall have a wider range of undesired events that threaten their functionality compared to banks and gas stations. Each is described in detail in the following subsections.

4.1. Banks

Banks vary in structure to include central banks, retail banks, commercial banks, investment banks, private banks, and credit unions. These organizations serve different consumer bases to include community members (individuals), businesses, and larger commercial entities. They also differ in the structure; members take ownership in a credit union, whereas larger banks rely on a top-down structure. This aside, primary products remain the same: (a) loan services (car, home mortgage, credit lines), (b) transactional accounts (checking and savings) and their maintenance through withdrawal services, and (c) debit, credit, and Certificate of Deposit (CD) services. Common supplemental

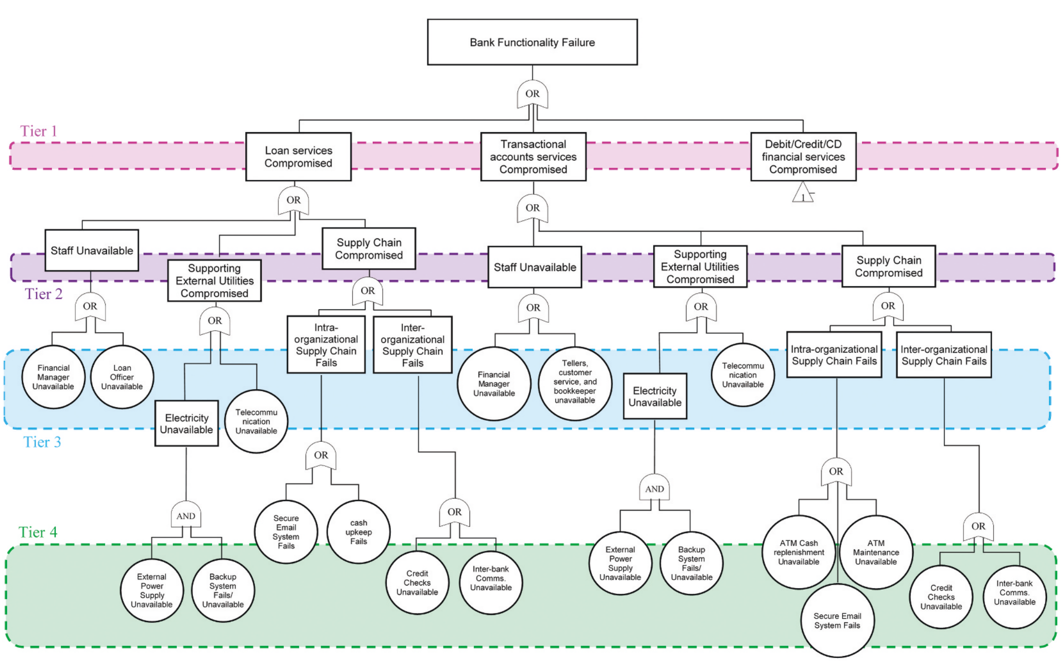

Figure 7. Fault tree of functionality loss of a bank.

services occurring often include investment consulting, wealth management, and safety deposit boxes as secondary products (Shekhar & Lekshmy, 2013). Taking the primary products into consideration, the generic fault tree from Figure 5 is adapted for banks in Figure 7. A functional bank is able to provide its primary products: transactional accounts services, loan services, and debit, credit, and CD services. For brevity, the branch corresponding to debit, credit, and CD services is not shown here, as it is essentially identical to the FT branch for loan services. The FT in Figure 7 only specifies events that are critical for the bank's functionality in the aftermath of a disaster. The FT excludes events associated with the compromising of physical space and physical access as non-critical fault events. This is directly tied to the advent and extensive use of online banking services and the popularity of ATMs for withdrawals. In this respect, the value of L_1 would be zero which means the Intrinsically Operable state will be omitted from the post-disaster functionality states of a bank. The events beneath supporting external utilities are modified in Tier 3 and Tier 4; the events of water, wastewater, and gas unavailability are excluded since they are connected to the physical space and thus not critical for the bank's functionality. Electricity and telecommunications are still included for the use of the Electronic Payment Network. The Tier 2 event of staff unavailability remains unchanged, highlighting the significance of financial managers, customer service and tellers, and loan officers to the service delivery and functionality of banks. Also, both intra-organizational and inter-organizational supply chains are considered critical for a bank's functionality. Any disruption in the replenishment of ATM cash, ATM maintenance, or cash upkeep as the intra-organizational supply chain can compromise the availability of withdrawal services. Similarly, inter-organizational supply chains are required for credit checks or inter-bank communication. Nonetheless, it is important to note the physical structure and external utilities are still required for a typical bank to be fully functional. Staff needs a physical space for long-term work, and a neutral meeting point for in-person services such as wealth management, investment consulting, and safety deposit boxes is undeniable.

Banks can also temporarily change their primary products. For example, after a disaster, a bank might still service existing customers whilst shifting to disburse Small Business Administration loans for recovery needs. This change in primary products is important for understanding the role financial institutions play in community functionality in short and intermediate-term, dynamic financial capital.

4.2. Gas Stations

The products of a gas station include the provision of automotive fuels (such as gasoline, diesel, gasohol), motor vehicle parts (e.g., lubricants, filters, etc.), restroom services, and some groceries, oftentimes drinks and snacks (BLS., 2020). Although gas stations might be a primary grocery supplier in some communities, the primary products of gas stations are the retail sale of fuel and lubricant for motor vehicles. Gas stations are often small employee-based organizations that do not require staff with technical degrees and almost always offer self-service and a pay-at-the-pump system. On the other hand, gas stations' procurement and distribution of fuel ties them to a physical space, and make them a supply chain-reliant organization. Thus, physical space, access, supporting external utilities, and supply chain, due to their interdependence, are critical components of a functional gas station, as shown in Figure 8. In this example, 25% is an appropriate estimate of the organizational functionality percentage associated with the Intrinsically Operable state (L_1) of a gas station. The FT in Figure 8 solely considers the events that are essential for the delivery of the primary products of a functional gas station. The FT includes all events associated with the compromising of physical space, physical access, and supply chain as they are critical fault events. Any type of structural damage to filling stations or non-structural damage to self-service facilities (such as failure of payment systems, oil suction systems, and gas pumps) can seriously compromise the physical space. The supply chain can be disrupted through failure in either external supply resources of fuel and lubricants or intra-organizational distribution systems. The functioning of pumps and pay-at-the-pump systems also depend on supporting external utilities of electricity and telecommunications; these events are included in the FT in Figure 8.

4.3. Schools

Schools are considered as a third and final example organization. Schools (K-12 and higher education) contain the most intra-archetype variation of the three organizations covered here. Schools vary considerably in size, organizational structure, and physical space. For example, smaller elementary schools can sometimes exist in one building, while larger campuses contain several buildings and many levels of staff and faculty to coordinate hierarchy within (Ungar et al., 2019). Figure 9 provides the fault tree for the functionality loss of a mid-sized K-12 school.

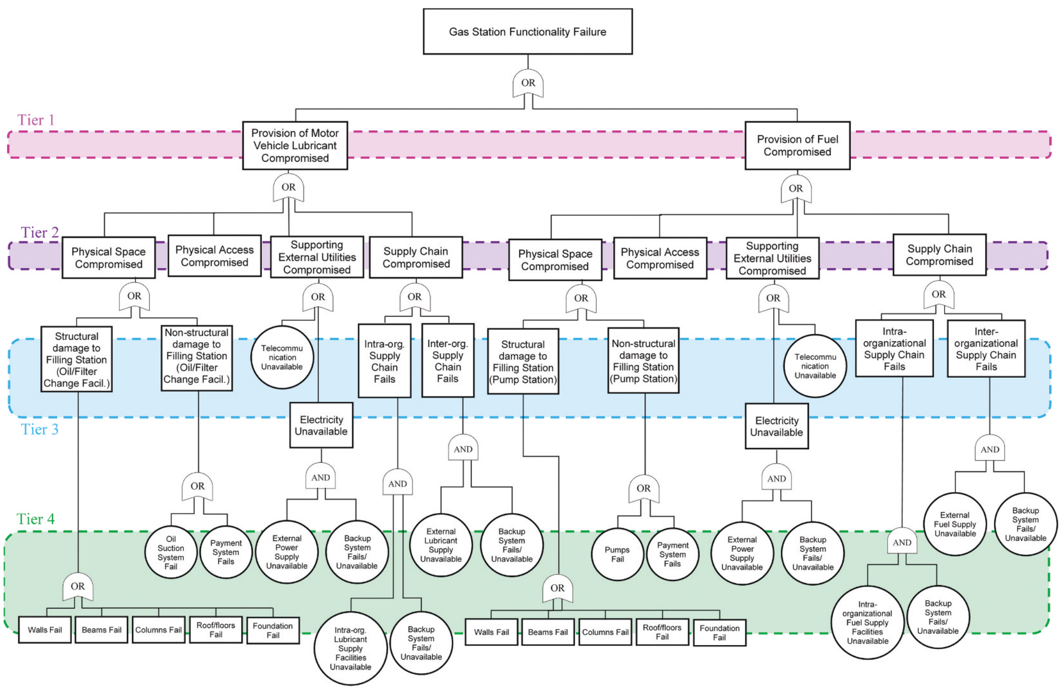

Figure 8. Fault tree of functionality loss of a gas station.

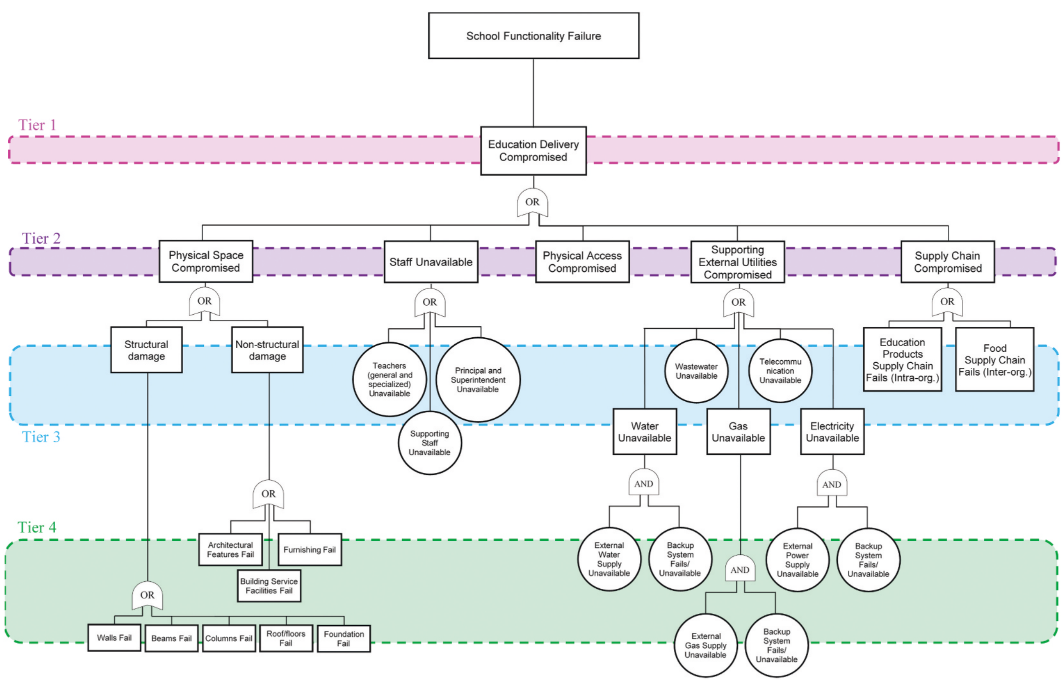

Figure 9. Fault tree of functionality loss of a mid-size K-12 school.

Schools exist to provide students with products of education, food, and recreation. Schools are highly staff-reliant, with generalized and specialized teachers being the main implementer of the products. Specialized teachers refer to those that require additional training and licensure, such as teachers who assist in teaching students with learning disabilities or technical coursework. Principal and superintendent availability becomes crucial to decision-making, advancement for the district, and any disciplinary action. Supporting staff are also vital to student well-being through food delivery, health services, and administration. So, too, is the supply chain to keep education products, food, and health items in stock at the school's location. In this case, the FT gives an estimate of 20% for the value of L1 in schools.

While the physical space, physical access, and external utilities are essential for a school's functionality, the basic objective of education can occur online, as exemplified through the COVID-19 pandemic and subsequent online-based education. Still, the quality of educational product delivery and schools' (and students') capacity to move online become serious limitations. This underscores a school's reliance on physical space while recognizing the flexibility and importance of at-home back-up space when the school's physical space is compromised. Also, when planning for community resilience, it is important to consider how the products of an organization may change during a disaster. For example, in addition to providing educational services, school buildings serve another primary role after disasters: the role of emergency shelters (McArdle, 2014; Mutch, 2014). In this second case, the physical space is extremely important, as well as physical access and supporting utilities.

5. Step-by-Step Procedure for Community Resilience Evaluation

Summarized below are the basic steps of a proposed practical framework to evaluate the post-disaster resilience of a community using the organizational functionality and community capitals concepts.

(1) Define a set of quantifiable metrics for each community capital (except built capital) regarding the existing organizations' products. For example, one scale for measuring social capital, particularly when it comes to organizations, is the *community housing capacity* which can be offered by single and multi-family dwellings, shelters, and hotels following a disaster.

Calculate the expected capacity of individual organizations contributing to the desired community capitals at the time t after the event using the relevant metrics defined in step 1, as:

$$ET[c(t)|e] = [Q(t,e)][c(t)|\bar{e}]\left[\frac{L_3 - L_2}{100 - L_2}\right] \quad (7)$$

where $ET[c(t)\,|\,e]$ is the expected capacity of the individual organization concerning metric k at time t after given disruptive event with demand e; $[Q(t,e)]$ denotes the probability of that organization becomes functional before time t which can be calculated by Equation (5); $[c(t)\,|\,\bar{e}]$ is the capacity of the individual organization concerning metric k at time t if the disruptive event does not happen; L_2 and L_3 are the percentage of functionality determined for Fully Operable and MALF organizations, respectively.

Calculate the expected capacity of each metric at the community-level by aggregating the expected capacity of the individual organizations computed in step 2, as

$$C[c(t)|e] = \sum_{j=1}^{n} (ET[c(t)|e])_j \quad (8)$$

$j = 1, 2, \ldots, n$
where $C[c(t)\,|\,e]$ is the expected capacity at the community-level concerning metric k at time t for the given disruptive event with demand e and is aggregated for n organizations that contribute to that metric capacity; all other parameters were previously defined.

Compare the expected capacity at the community-level considering metric k with community resilience and recovery plans and use the results to make more informed decisions that minimize the long-term recovery time of the community. Several approaches exist in the literature for community resilience planning and risk-informed decision-making (e.g.,(Nations, 2016)), but this is outside of the scope of this paper.

6. Conclusion

The need to rethink design goals in U.S. building codes to include functional recovery targets has gained significant traction in recent years. Designing for functional recovery should consider limit states for both safety and functional recovery time. Buildings are should not be considered as isolated structure, but as part of a community. As such, it is imperative to understand, measure, and evaluate how that building supports or otherwise contributes to various community functions and related capitals. This relationship can be understood through (1) the organization(s) residing in the building, and (2) how the products of the organization(s) support the community measured through the community capitals.

Organizations work as a lynchpin connecting the built capital to the other capitals. Communities need to ensure that their organizations will be recovered within an acceptable period to support short, intermediate, and long-term functional recovery goals. Therefore, the availability of a decision variable which links the community resilience objectives to the built environment functional recovery goals will result in more informed disaster risk mitigation and long-term recovery plans at the community level.

To that end, this paper has introduced the concept of organizational functionality, defining it as the quality in the performance of an organization, and its ability to offer its primary products. The concept advances research on community resilience planning and functional recovery design, and can be applied by researchers, practitioners, and policymakers. Importantly, organizations require physical and non-physical, or rational and irrational, components to function; the details of which are organization-specific. To validate organization-specific fault trees and quantify the contribution of organizations to the community, further research and data collection are required, which should include working directly with organizations. More research is needed to define explicit measures for the MALF and MDTP of an organization, and to develop a comprehensive library of fragility and restoration functions for the components of organization functionality.

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