

**Sustainability in Disaster Operations Management and Planning:
An Operations Management Perspective**

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ABSTRACT

Advancing the state of disaster operations planning has significant implications given the devastating impress of disasters. Operations management techniques have in the past been shown to advance disaster-planning efforts; in particular, much progress can be noted in its application in the advancement of short-term recovery operations such as humanitarian logistics. However, limited emphasis has been placed on the long-term development scope of disaster operations. This dissertation argues the need for a fundamental shift in the motivation of archetypal disaster planning models, from disaster planning modeled around the emergency of the disaster event, to that of the sustainability of the community. Consequently, the purpose of this study is to address three key issues in regard to sustainability in disaster operations and planning.

The first study of this dissertation (Chapter 3) focuses on describing disaster operations management and planning in its current state, examining features unique to sustainability in this context, and finally developing a planning framework that advances community sustainability in the face of disasters. This framework is applied in the succeeding quantitative studies (Chapter 4 and Chapter 5).

The second study in this dissertation (Chapter 4) extends the sustainable planning framework offered in Chapter 3, using mathematical models. In particular, the modeling contributions include the consideration of multiple possible disaster events of single disaster type expected in a longer-term decision horizon, under integrated disaster management planning that is geared towards sustainability. These models are assessed using a mono-hazard scenario generator. A pedagogical example based on Portsmouth, Virginia, is offered.

The last study in this dissertation (Chapter 5) extends the application of quantitative models to account for the ‘multi-hazards’ paradigm. While Chapter 4 considered multi-event analysis, the study was limited to a mono-hazard nature (the consideration of only one type of hazard source). This study extends analytical models from mono-hazard to multi-hazard, the consideration of a range of likely hazards for a given community. This analysis is made more complex because of the dependencies inherent in multiple hazards, projects, and assets. A pedagogical example based on Mombasa, Kenya, is offered.

DEDICATION

*“A society grows great when old men plant trees whose shade they know they shall never sit in”
~ Greek Proverb*

This dissertation is dedicated to scholars everywhere who have dedicated their life to mentoring and imparting a passion for life-long learning, fully aware that they may never directly benefit from the ROI. It is in this spirit, that this dissertation is also dedicated to ‘Batman’, who espouses these values and of whom I have grown to have much respect for. True to the saying, “good things come in threes”, this dissertation is finally dedicated to my wife Linda, whose intellect I admire, and whom I dearly love.

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*Consummatum est....
.....gratia Dei*

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CHAPTER 1: INTRODUCTION

Over the past century, demographic trends in urban locales have invariably led to the concentration of capital investment around these human ‘hotspots,’ unfortunately also resulting in an increase in disaster vulnerability of humans, both socially and economically (Cutter, et al., 2008; Tierney, 2009). Unfortunately, disasters are a worldwide problem, and as shown in Figure 1-1, they are an increasingly costly one.

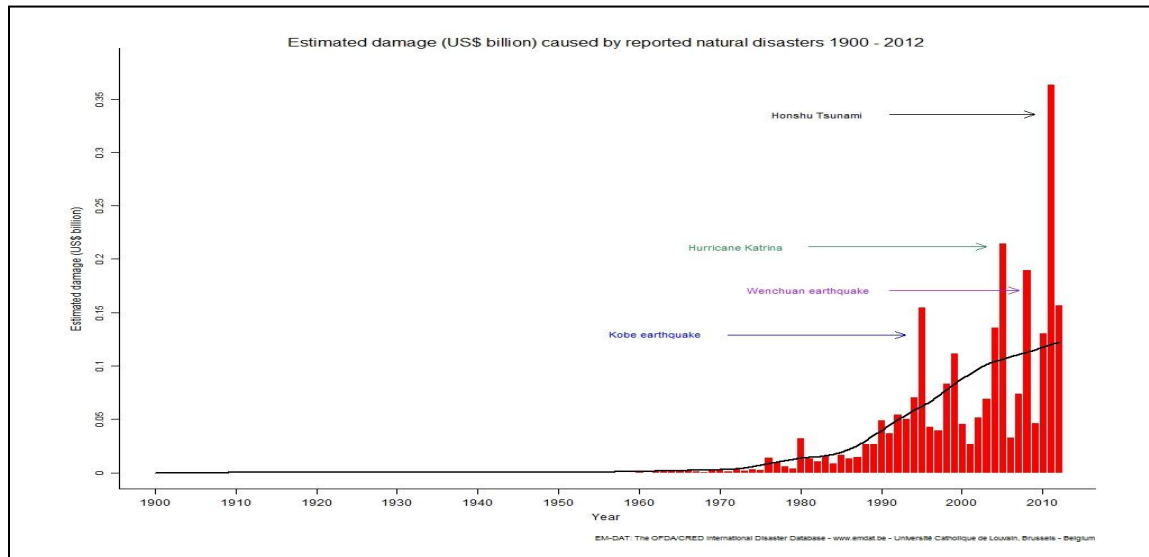


Figure 1-1. Increasing Costs due to Natural Hazards (EM-DAT, 2013)

With a progressively interconnected world under threat from disasters of increasing frequency, attributed to climate change, social unrest etc., and aggregated effect; it is critical to advance the state-of-the-art in disaster operations management. In particular, there is need to emphasize a more long-term and sustainably driven form of disaster operations divorced from the short-term urgency of relief focused management.

Disaster Operations Management, Resilience and Sustainability

Disaster operations management (DOM), commonly defined as a set of activities aimed at limiting initial disaster impacts and returning to a state of normalcy (Altay & Green, 2006), is a

significantly complicated process. Central to the complexity is its inherent socio-technical nature, consisting of a network of stakeholders working together under possibly conflicting goals, who must perform technical activities under temporal externalities. Technical activities associated with DOM are carried out in each of the phases of the disaster management cycle: Preparedness, Response, short-term Recovery (transitional stage between response and long-term recovery), long-term Recovery, and Mitigation. Activities carried out in the first three phases listed are focused on the immediate event (relief), while the last two phases are focused on long-term preparation and recovery (development). Thus when effecting overall planning for a disaster, managers should not ignore (i) the immediate, event-specific actions aimed at short-term emergency response and relief, which reflect the importance and urgency of alleviating immediate human suffering, or (ii) the long-term actions focused on bringing the community back to a state of normality and viability. Such long-term actions help the community become better prepared for the next disaster event, whenever it happens, reflecting the importance of stability (Holguín-Veras, Pérez, Jaller, Van Wassenhove, & Aros-Vera, 2013) and quality of life issues (Asprone, Prota, & Manfredi, 2014; Turner et al., 2003). As is evident from the earlier discussion, the DOM planning problem lends itself naturally to partitioning: (1) a planning model motivated around the disaster event's *emergency*, and (2) a planning model geared at long-term viability.

It is in the context of human suffering that length of recovery is absolutely critical. One useful measure for this is resilience as it focuses on a systems coping and recovery capacity for the sole purpose of reducing the time an entity is under stress (Zobel & Khansa, 2012). While resilience focuses on the disaster event, sustainability is far broader as it widens the focus from the disaster event to broader quality of life systems principal to a community's long-term

viability and stability. The objectives of sustainability include three dimensions: economic, environmental, and equity. Critically, sustainability is a locally driven process with emphasis placed on engagement - including community members' needs in the planning process.

Statement of the Problem

The ascendant research paradigm in disaster operations management has been that of the humanitarian organization as the decision maker. This is self-evident in the research published in the top operations management journals. This paradigm has two well-known underlying motivations: (i) The humanitarian organization is primarily focused on disaster relief. (ii) Power is in the hands of the donor, since they are the source of the 'capital flow'; the affected community does not have much input as the beneficiary. This has resulted in the typical emphasis of analytical research around the emergency of the disaster event. Although these motivations are well-grounded and important, in the long run there are three primary issues associated with this research stream.

The first problem area is that traditionally disaster planning is modeled around the emergency of the disaster event, rather than the sustainability of the community; this is quite evident when looking at both the qualitative and quantitative literature. However, while the sustainable literature in disaster operations raises real issues regarding tradeoffs and long-term community viability, the literature fails to offer a concrete framework with which to enable sustainability-driven disaster planning.

Secondly, most analytical models in disaster operations planning, given the first problem area, are motivated temporally around the immediate disaster event, rather than the long-term nature required in appropriate decision models, which employ a decision horizon. This

incongruence is exaggerated particularly when considering the cyclical and recurrent nature of natural hazards.

Finally, traditional disaster planning models motivated around a single hazard in isolation are inadequate especially since many regions in the world are vulnerable to more than one type of hazard (Kappes, Keiler, Elverfeldt, & Glade, 2012). For example, an urban city center such as San Francisco, CA, with a population close to 850,000 is at risk from wild fires, tsunamis, landslides, earthquakes, flooding, heat waves, and droughts (Ayyub, 2014). This inadequacy is prominent particularly given the context of climate change and the projected increase in the frequency of weather extremes, over the coming decades.

Objectives of the Study

The purpose of the first proposed study is to develop a DOM planning framework that captures the mechanisms and objectives central to sustainability and, in addition, to integrate the planning across the emergency and sustainability elements that exist in a DOM cycle. The scope of this research however is focused on the long-term sustainability of a community; as a result, the focus is expanded from relief-driven planning to broader system linkages external to the disaster event.

In the second suggested study, using the proposed sustainability driven framework as a guide, the paper proposes an analytical mathematical model analyzing resource allocation efficiency and the impacts of long-term decision policies, beyond the reaction of a single event epoch. This study however is limited to the mono-hazard problem (model only considering a single type of hazard but can include multiple events of this hazard). Several decision policies, under stipulated assumptions, are evaluated under a set of objectives specified by the community with the purpose of maximizing these community values and the speed of their recovery. This

study furnishes experimentation on the effect of certain decision policies on community value, using a simulation model that generates various disaster scenarios based on environmental uncertainty.

Finally, in the third study, the sustainability driven framework is extended to explore the impact of a ‘multi-hazards’ (MH) approach to disaster planning (the term used by FEMA is ‘All-Hazards’). This study extends the archetypal focus on a single hazard event in isolation, to a range of likely hazards. Furthermore, institutions like FEMA (FEMA, 1995) and the UN (UN-ISDR, 2005) have encouraged the use of a multi-hazard approach to risk analysis. The MH prism augments decision models by enabling the inclusion of interdependencies across multiple hazards both in terms of actions taken and the hazard impact on targets (i.e., critical assets, geographical locations or regions, etc.).

Research Methodology

The research methodologies employed in this dissertation are both quantitative and qualitative in nature. The quantitative aspect of this research includes the application of a resource allocation problem formulated as a linear programming (LP) model with piecewise linear approximations of the resilience objective. The LP formulation is developed for the mono-hazard problem (Chapter 4). A mixed integer multi-objective programming formulation is employed for the multi-hazard form of the problem (Chapter 5), with similar piecewise linear approximations for the objective functions. The performance of various decision policies is assessed under a disaster scenario generator using discrete-event simulation for both studies.

The qualitative phase of this dissertation is the development of a sustainability-based planning framework for DOM. The framework is developed from the assimilation and synthesis of theories, models, and various decision frameworks that are published in current literature.

Enhancements to this framework are/will also be introduced based on results of our mathematical models.

Scope and Limitations

Disaster operations management has traditionally been the purview of hazard and emergency management researchers. Admittedly, the recent emphasis on this area by POMS (the Production and Operations Management Society) has resulted in the application of operations management / operations research techniques, in this overtly complex field. To keep the exploration of this dissertation manageable, this research focuses mainly on disaster operations geared towards community sustainability. As such, the focus of the research is at the strategic and tactical level of planning. Explicitly, this work does not cover operational and day-to-day decision making in emergency management. Moreover humanitarian operations geared at the emergency of the disaster event such as relief-based humanitarian logistics is not considered (including its strategic form, such as asset prepositioning).

This research does not provide a unique global solution that prescribes a specific policy to a community for adoption. The studies' main emphasis is limited to analysis and not prescription. The objective of this dissertation is to propose a novel and better method of disaster planning. The mathematical models developed capture general relations and thus provide the first cut at what should be the right direction in assessing decision policies. The models can be enriched to capture more disaster realities, but this is beyond the scope of this research. Specifically in regards to the mathematical formulations, resources are modeled assuming that they are static. In reality, however, disaster resources are dynamic both temporally and spatially. Availability of resources in itself is a significant area of research in the disaster management field, as noted in Starr and Van Wassenhove (2014). Furthermore, the resource allocation model

in this dissertation assumes that the performance of mitigation options is linear with their level of completion. Also, the cost functions of decision options are assumed convex and linear with the level of activity decided, and continuous. In reality, cost functions are often non-linear due to monetary discounts specified at certain levels of investment.

Contributions of the Research

The research in this dissertation makes five primary contributions:

- It provides an extensive literature review on the multi-disciplinary nature of disaster operations management planning, with a specific focus on sustainability and resilience.
- It develops a DOM planning framework that emphasizes community sustainability.
- It provides mathematical planning models embedded in a simulation model, to efficiently allocate resources to possible sets of intervention strategies, for each community devised policy.
- It explores the ‘multi-Hazards’ approach to disaster management planning and specifically models interdependencies across mitigative/recovery actions on multiple hazards.

Unification of Chapters

This dissertation, upon the supervision of my advisor, Dr. Loren Rees, has been written as a series of three separate journal articles all under the thematic umbrella of disaster development operations, its management and planning. Accordingly, Chapters 3, 4, and 5 are formatted as journal articles and are meant to stand on their own - each with its own title page, abstract, and references. However, references from each chapter have been alphabetically compiled at the end of the dissertation to provide one, exhaustive bibliography.

The unifying theme in this dissertation is specifically sustainable disaster operations management planning. Chapter 3 emphasizes the development of a planning framework to

promote community sustainability after the onset of a disaster. Chapter 4 extends the framework developed in Chapter 3 into analytical models. The mathematical model is enhanced with a pedagogical example that is based on Portsmouth, VA. Chapter 5 extends the analysis conducted in Chapter 4 by addressing the impact of including a ‘multi-Hazards’ approach to disaster management planning. While each of the three chapters mentioned above is written separately, they are all associated in addressing disaster operations planning aimed at community sustainability.

Plan of Presentation

This chapter has served as an introduction to development-focused, as opposed to relief-oriented, disaster operations management planning. It has identified the need for disaster operations planning driven by the objective of community sustainability rather than disaster event emergency.

Chapter 2 is a literature review in the areas of disaster operations management and its foundational paradigms, sustainability, resilience, decision support systems, and solution methodologies. This review establishes the need for a decision framework that supports community sustainability in the management of natural hazard risk.

Chapter 3 presents a disaster operations planning framework, aimed at community sustainability, which can be used to evaluate various decision policies. With a disaster model defined, Chapter 4 proceeds to develop appropriate analytical models that can support decision-making and evaluation. The model is explicated using discrete event simulation based on a pedagogical example of Portsmouth, VA. Chapter 5 examines the inclusion of a multi-hazard approach to decision making in the context of multiple hazards.

Conclusions will be drawn and future work outlined in Chapter 6 of the completed dissertation.

CHAPTER 2: LITERATURE REVIEW

This literature review primarily provides an overview of research in regards to sustainable disaster operations management. As part of this review, discussions on disaster management paradigms are offered, which to some degree are shaped by the disaster context. Discussions on disaster operations and its subset – humanitarian operations, are also offered in this review.

Sustainable disaster management is unique in its emphasis of elements of resilience, community engagement, and long-term planning. As such these issues will also be discussed in this review. This literature review also covers the methodological areas of Decision Support Systems (DSS), Geographic Information Systems (GIS), mathematical programming, simulation, and fuzzy sets, as these will be variously invoked in implementation of the new model.

1.0 DISASTERS

The intrinsic nature of a disaster is central to any discussion on disaster management. To the layperson, disasters, emergencies, and hazards may be identical, but the discussions on these terms are far more intricate. Moreover, the various diverse philosophical paradigms by which disasters have been defined have included: functionalism, social constructionism, postmodernism, conflict-based theories, and political economy theories (Mileti, 1999; Pearce, 2000; Tierney, Lindell & Perry, 2001). These definitions are borne out of the diverse philosophy of science perspectives rather than the physical characteristics used to associate with disasters. However, nominal definitions that focus on physical characteristics provide an underlying framework with which to operationalize the definition (Perry, 2006).

1.1 Definition

While the definition of the term ‘disaster’ is contentious and researchers are not united on a single definition (Holguin-Veras et al., 2012; Quarantelli, 1998a), the diverse paradigms

motivating discussions in this area are informative. Interested readers are encouraged to examine publications such as Perry (2005, 2006) and Quarantelli (1985, 1998a), which provide a comprehensive discussion on the disaster term and underlying assumptions.

The nominal disaster definition used in this dissertation, consistent with recent adaptations in the operations management literature as in Holguin-Veras et al. (2012), is adapted from Pearce (2000, p. 22): “... a non-routine event that exceeds the capacity of the affected *community* to respond to it in such a way as to save lives, to preserve property, and to maintain the social, ecological, economic, and political stability of the affected *community*.” In this dissertation the original term “area/region” is replaced with “community” (italicized), so as to frame the disaster definition to those disasters that affect human populations – “although the vast majority of disasters impact communities, not all do” (Quarantelli, 1998b, p. 1). Accordingly, this dissertation defines community as a group of people characterized by a common geographical boundary, small enough to be appropriate for participatory decision-making. This definition of community is consistent with Mileti (1999).

1.2 Disaster Characteristics

In general, much of the scholarly work in the disaster and humanitarian operations management field highlights the physical characteristics of the disaster and its impact. These tangible characteristics provide the motivation for context discussion when comparing commercial models with disaster/humanitarian ones. These tangible dimensions can broadly be split into four categories.

1. Temporal (time related characteristics of disasters)

- a. *Disaster Onset* (Apte, 2010; Van Wassenhove, 2006): Refers to the rate of a disasters arrival. Those disasters that arrive suddenly are referred to as rapid

onset, e.g. earthquakes, cyclones, floods. Disasters that take time, months to years, are referred to as slow onset or emerging, e.g. droughts, famine. (rapid onset vs. slow onset)

- b. *Duration* (Waeckerle, 1991): Refers to the length of time the disaster continues to impact people. Some disasters have an immediate impact like earthquakes, while others have an extended or sustained impact like wars. (immediate vs. extended)
- c. *Patterns/Predictability* (Apte, 2010; Van Wassenhove, 2006; Waeckerle, 1991): Refers to the time-series patterns that some disasters exhibit. Some natural hazards have cyclical patterns and are easier to predict, e.g. Nor'easters, or forest fires during the summer, while some disasters are difficult to predict, e.g. earthquakes. (cyclical vs. random)
- d. *Frequency* (Waeckerle, 1991): Refers to regularity of the disaster. Some disasters are rare (e.g. black-swan type disasters) and others are common (e.g. tornados in the Mid-West)

This dissertation focuses on rapid onset disasters with immediate impacts.

2. Spatial (geographic and space related characteristics of disasters)

- a. *Affected Region* (Waeckerle, 1991): Refers to the disasters spatial impact. Some disasters are localized and affect a city, e.g. the tornado that struck Joplin, Missouri, while other disasters can affect multiple states (e.g. Hurricane Sandy). It is critical to note that due to the highly interconnected global supply chain, a local disaster can also have far reaching global impacts. For example, the Tohoku earthquake off the Japanese coast resulted in a Tsunami, which basically took

down much of Toyota's supply chain and impacted Toyota subsidiary firms all over the world.

3. Experiential (the experience of the disaster's impact):
 - a. *Type of Impact*: A disaster can have impacts that affect a community across multiple dimensions. These include and are not limited to physical, social, psychological, and environmental impacts.
 - b. *Scale of Impact*: Based on the scale of a disaster's impact, disasters can be characterized as a catastrophe, a disaster or an emergency (Holguin-Veras et al., 2012).
 - c. *Community Affected*: Some communities already have experience with disasters and have certain capacities to better deal with disaster impacts unlike those who are struck with a disaster for the first time (Faulkner, 2001). More so, there can be some inherent community characteristics that may moderate some of the impact. These characteristics could be socio-economic, political, cultural, demographic, organizational etc. (Faulkner, 2001).
4. Cause / Source (Disasters can be initiated by man/technology or nature)
 - a. *Natural Disasters* (Waeckerle, 1991): Disasters can be initiated by nature such as natural hazards (which can be further split based on type of nature e.g. geophysical (earthquakes, tsunamis, volcanos), hydrological (floods), climatological (drought, extreme weather), biological (epidemics)).
 - b. *Man-made / Technological Disasters* (Waeckerle, 1991): Technological or man-made disasters are a result of human interaction e.g. (terrorism, wars, famine,

industrial accidents, e.g. Chernobyl). It is under this definition that some authors argue that epidemics are man-made disasters.

Sociologists (e.g. Quarantelli) have indicated that a disaster ceases to be one if humans are not affected; in other words disasters are inherently social in nature. Reasonably then, Cutter underscores the importance of shifting the focus from the disaster itself to a community's vulnerability or resiliency to it (Cutter, 2005). Cutter shifts the onus from understanding disasters to managing their impacts on humans. As noted above, disaster impacts are unique to the disaster context and disaster management has to adapt to the context. For example, approaches developed to deal with rapid onset disasters like floods differ from those developed to deal with slow onset disasters (Apte, 2010). See section 2.4 for factors that alter the management context.

2.0 DISASTER OPERATIONS MANAGEMENT

Disaster operations is a broad term that involves all types of activities initiated to respond to a disaster, with the end objective of bringing the affected community (or system) to some state of normalcy. These activities can be carried out by government agencies (federal, state or local), the affected community, volunteers, and humanitarian organizations. In this section we discuss in broad terms, relationships, disaster management paradigms, and their resulting implications. Section 3.0 offers a more nuanced perspective, that of humanitarian operations, in which disaster operations is carried out by humanitarian organizations.

2.1 Definition

Disaster operations management (DOM) is commonly defined to be “the set of activities that are performed before, during, and after a disaster with the goal of preventing loss of human life, reducing its impact on the economy, and returning to a state of normalcy” (Altay & Green, 2006, p. 476). Typically, definitions of disaster management (DM) are in terms of its operational

outcomes (see, e.g., Altay and Green (2006), Lettieri, Masella and Radaelli (2009), and Quarantelli (1988)). Such definitions often include language to indicate that DM is a series of activities that has the purpose of alleviating disaster effects. Pearce (2000) provides a subtle addition to these delineations by alternatively emphasizing disaster management as a process of establishing goals with an intended operational outcome. (This is consistent with the spirit in which Drucker defines management in the business literature (Greenwood, 1981)). Accordingly this dissertation adopts Pearce’s (2000, p. 28) definition of DM, defining disaster management as the process of establishing common goals between actors for the purpose of planning for and dealing with disaster effects, such as limiting the future impact of disasters and recovery back to a state of normalcy. Note that this characterization emphasizes both the outcomes and the establishment of common goals as central to the DM process. Moreover, this dissertation frames DM to those issues of disaster operations.

2.2 Management Phases

Central to the complexity of the disaster operations management (DOM) process is an inherently socio-technical process, comprised of a network of stakeholders working together under possibly conflicting goals, who must perform technical activities under temporal realities. These temporal realities dictate the appropriate objectives for the appropriate technical activities. Figure 2-1 highlights these temporal realities.

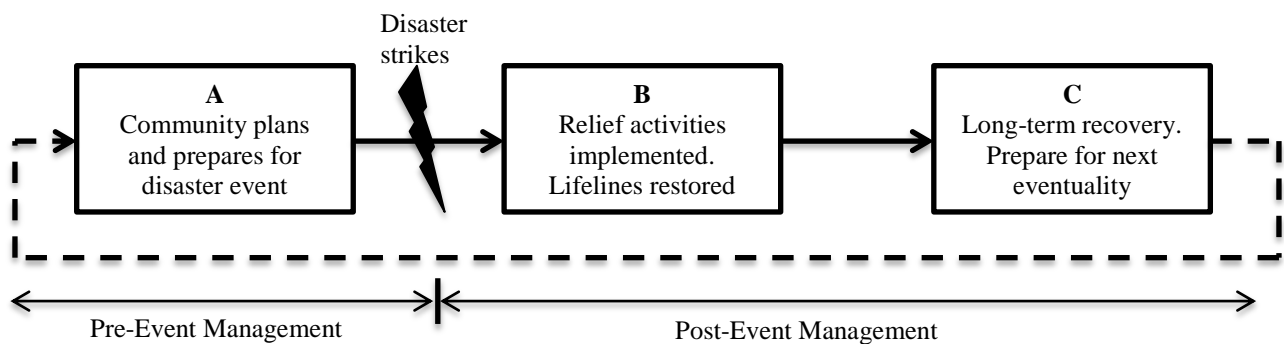


Figure 2-1. Disaster Management Timeline

The disaster management timeline includes planning and preparing for the disaster event, and once the event strikes, providing relief-oriented services, after which the emphasis shifts to long-term recovery. The affected community learns from this experience and prepares itself for another eventuality. It is critical to note that technical activity cluster ‘A’ (see Figure 2-1) is dependent on early warning and disaster communication systems. As such, if early warning systems do not exist, much of ‘A’ is bypassed and there is far more work to be done in ‘B’.

Relief oriented activity clusters are motivated around the emergency of the event whose objectives are focused on suffering reduction, while development oriented activity clusters are motivated around the sustainability and viability of the entity of concern (e.g. affected community). From the view point of the humanitarian organization, Starr & Van Wassenhove (2011) indicate that technical activity cluster ‘A’ and ‘B’ are relief-oriented (Humanitarian Relief Operations – HRO), while technical activity ‘C’ is development-oriented (Humanitarian Development Operations – HDO).

Traditionally, these technical activities have been classified under management phases of the disaster management cycle: Mitigation, Preparedness, Response and Recovery (Altay & Green, 2006; Tommasini & Van Wassenhove, 2009). Activities carried out in the first two phases, listed above, are focused on minimizing social, economic and physical impact. These activities include improving flood defense improvement, land use planning, and development of event response plans (Berke, Kartez & Wenger, 1993; Godschalk, 2003). Immediately after a disaster, the response phase, emergency responders initiate activities that are focused on managing after-disaster effects, evacuation, search and rescue, and movement of lifeline support equipment (Altay & Green, 2006, Lettieri et al., 2009). Activities in the recovery phase are split into two sub-phases: short-term and long-term (Holguin-Veras et al., 2013; Tierney et al., 2001).

Short-term recovery refers to the transitional stage between response and long-term recovery. This stage includes activities such as debris removal and restoration of lifelines (e.g. power). Long-term recovery is focused on returning the affected community to a state of normalcy (can be better or worse than its prior state). This includes rebuilding, financial support of businesses, and developing partnerships and networks for long-term success (Berke et al., 1993; FEMA, 2011).

Similarly, under the traditional disaster management cycle description, activities carried out in the Preparedness, Response, and short-term Recovery phases are motivated around the immediate disaster event (immediately before, during, and immediately after the event – see A and B in Figure 2-1), whereas activities carried out in the Mitigation and long-term Recovery phases are focused on the long term (see C in Figure 2-1).

2.3 Basic Elements and Relationships in Disaster Management

A scan of the emergency/disaster management literature in various disciplines (Bigley & Roberts, 2001; Faulkner, 2000; McLoughlin, 1985; Mendonça, 2007; Pearson & Clair, 1998; Straub & Welke, 1998; Waeckerle, 1991; Wallace & De Balogh, 1985) highlights four key classes involved in disaster management, from the perspective of the incident manager. Table 2-1, offers a sample breakdown.

(i). The triggering event or disaster(s): The characteristics of the event/disaster provide the context in which management occurs. For example, the disaster may be rapid on-set with an immediate impact resulting in an environment in which time pressure exists.

(ii). Region/community or critical asset(s) affected: This refers to the community/system experiencing the disaster.

(iii). Intervention strategies implemented: Refers to the sets of activities which the responding agencies can implement in light of the disaster, given available resources.

(iv). Available resources and accessible community capacities: Refers to the human, material, organizational capacities etc., which can be used to address the disaster impact.

The four elements listed are irreducible; other elements are present but are collapsible into the four elements highlighted. For example, humanitarian organizations are part of the disaster management process but can be collapsed under available resources or capacities, as they provide service to affected communities.

The relationships between these elements can also be summarized into six irreducible forms of interaction relationships, as presented in the Venn diagram shown in Figure 2-2.

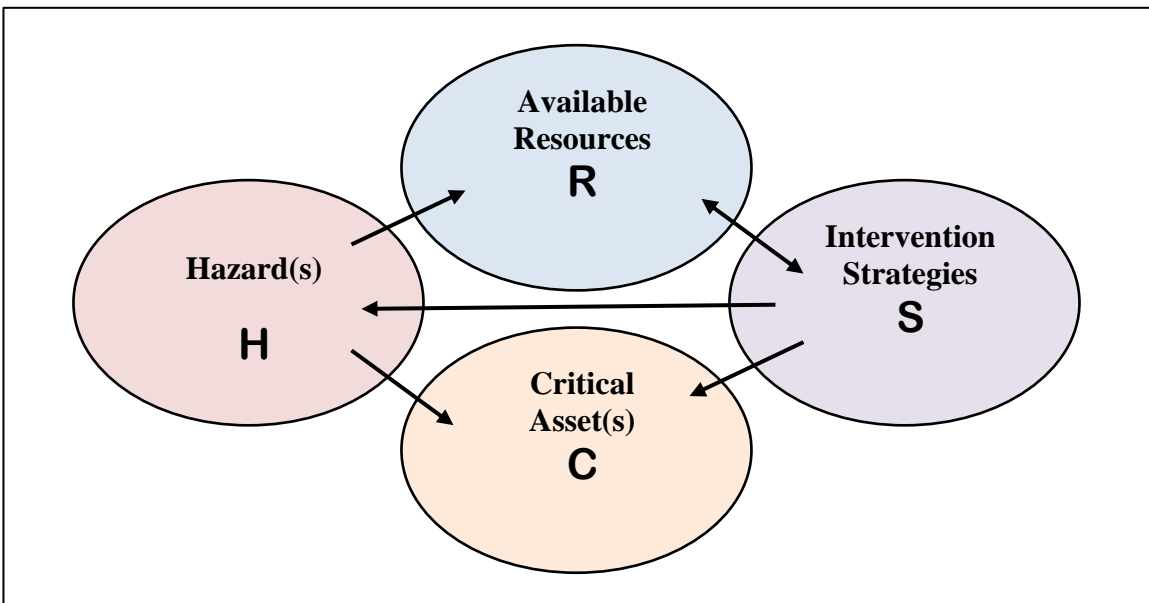


Figure 2-2. Relationships between Disaster Management Elements

Depending on the hazard's characteristics, its effects impact susceptible communities/critical assets, and available resources and capacities. Intervention strategies implemented, also dependent on disaster characteristics or its timeline, are geared towards securing critical assets and resources in terms of limiting hazard impact, disaster relief, and

recovery. In some cases, the strategy implemented can deter or prevent a disaster. For example, in the case of an intentional attack, as highlighted under the information systems domain in table 1, intervention strategies can *deter* the hazard itself – resulting in a mechanism in which an intervention affects the hazard itself. Finally, the application of intervention strategies is limited in scope and extent by available resources and capacities. Note: The radii of the circles, as symbolized in Figure 2-2, do not refer to any variable scale and are irrelevant to this discussion.

Table 2-1. Domain Specific – Crisis Management Model Elements

Natural Hazards	Brief Summary (Management Model)	Model Components
<p>McLoughlin (1985) Journal: <i>Public Administration Review</i> Citation Count: 162+</p>	<p>Step 1: conduct hazard analysis. This includes identification of potential hazards, determination of hazard descriptors (probability, intensity, location), and determination of resulting damages both on community and resources at risk. Step 2: Determine resources and capacities available for emergency management. Finally, carry out intervention strategies as defined by mitigation, preparedness, response, and recovery actions.</p>	<p>Natural Hazard, Community & community resources, Resources and capabilities available, Intervention strategies</p>
Information Systems	Brief Summary (Management Model)	Model Components
<p>Straub and Welke (1998) Journal: <i>MISQ</i> Citation Count: 726+</p>	<p>First recognize security problems, conduct risk analysis (separate business risk from systems risk), evaluate various intervention alternatives (deterrence, prevention, detection and recovery), make decisions, implement and finally monitor and control as a means of feedback to the prior model components.</p>	<p>System hazard, System, Intervention strategies, Feedback system</p>
Organizational Management	Brief Summary (Management Model)	Model Components
<p>Pearson and Clair (1998) Journal: <i>Academy of Management Review</i> Citation Count: 985+</p>	<p>Prepare for crisis as influenced by industry regulations and institutional practices. Once a crisis event occurs, a planned or an ad-hoc response kicks in. There are both individual and collective reactions to the crisis; similarly responses aimed at recovery and adjustment happen at both individual and organizational levels. The outcome of the disaster results in either a degree of success or failure, as on a continuum. Outcomes are multi-dimensional including, among others, business resumption, effects on reputation, and resource availability for crisis response.</p>	<p>Crisis, Business (collective) and business agents (individual), Intervention strategies (planned or ad-hoc), Resources for response</p>

2.4 Factors that Alter the Disaster Management Context

Determining the appropriate context requires that the factors listed be weighed on the whole rather than individually. The factors include:

Decision Maker: The perspective of the decision maker determines the objectives, and the scope of the work. The focus and the objective of the humanitarian organization (HO) can and should broadly be summarized under suffering alleviation (Holguin- versa et al., 2013). For example, once the disaster strikes, the HO focuses on logistics – movement of critical resources such as food, clothes, etc., to the beneficiary through available transportation routes. In addition, when the HO makes strategic decisions (e.g. pre-positioning of assets) the objective is still to alleviate suffering once the disaster strikes. Furthermore, in the HO perspective, the donor has all the power, while the beneficiary has none. However, if the decision maker is the affected community (aka beneficiary in HO ‘lingo’), then the end goal is to not only to respond to the disaster but to be better prepared for the next one through prevention, mitigation, and long-term recovery. The objective is long-term community viability and stability; in such a perspective, the community has and should have the power.

Disaster Phase: As highlighted in Figure 2-1, the stage or phase of the process also determines the type of action required and objectives espoused. For example, regardless of the decision maker (HO or government or affected community), if the disaster has just occurred, the focus is on disaster relief and suffering alleviation. However, if initial disaster relief work is completed, more long-term development oriented projects are considered. (Relief vs. Development).

Disaster Characteristics: The physical characteristics of a disaster affect the context in which disaster management can be applied. For example rapid-onset disasters are characterized

by a large number of activities, with different resource needs, that need to be carried out under temporal urgency (Schryen, Rauchecker, Comes; 2015); this is not the case for slow onset disasters such as drought –there is no immediate time pressure. Another intuitive example, a disaster with immediate impact (e.g. earthquake) duration is managed differently than one that has an extended duration (e.g. famine).

DM paradigm: The paradigm embraced by the decision maker (in this case, affected community), determines the type of management embraced. For example, a community that emphasizes a comprehensive emergency management based paradigm is motivated by the immediate disaster; this is reflected by the emphasis on disaster relief and short-term recovery. This type of management is reactive as there is no emphasis on the next disaster or preparation for it. See section 2.5 for more details.

2.5 Disaster Management Paradigms

Over the past three decades, various paradigms have been proposed to advance disaster management research and its praxis, including: comprehensive emergency management (CEM), disaster resistance, vulnerability, resilience, and sustainability (McEntire, 2005; McEntire, Fuller, Johnston & Weber, 2002). For an extensive comparison see McEntire et al. (2002).

2.5.1 CEM

The CEM paradigm, though noteworthy in its attempt at integration and comprehensiveness, focused too much on the emergency of an event, consequently it was generally limited to those actors directly involved with the emergency - emergency managers, first responders, etc. (McEntire et al., 2002).

2.5.2 Disaster Resistance

Conversely, disaster resistance was aimed at reducing a community's exposure to hazard risks, specifically converging on mitigation and related actions. However this emphasis did not account for the reality that regardless of mitigation, communities have experienced and continue to experience extreme events, and so there is still a need for response and recovery (McEntire et al., 2002).

2.5.3 Disaster Resilience

Disaster resilience, unlike disaster resistance, recognizes that disasters happen, and as such, decisions should be geared both at resistance and at recovery (McEntire, et al., 2002). However, some contention exists among researchers regarding the definition of resilience. Discussions on resilience definitions and conceptualizations are offered in section 4.0.

One limitation of the disaster resilience paradigm is that its focus is specific to the immediate event – it emphasizes a prompt return to a state of normalcy (McEntire et al., 2002). However, there has traditionally also been a strong linkage between the concepts of sustainability (beyond the immediate event) and resilience, though disagreements regarding their exact relationship exist. Resilience as a dimension of sustainability is the form of relationship that this dissertation adopts as supported in the following publications (Asprone, Prota & Manfredi, 2014; Mileti, 1999; Pearce, 2003; Smith & Wenger, 2007); specifically, the view here holds that sustainability is a broader paradigm while resilience is specific to the extreme event (Asprone et al., 2014; Turner et al., 2003).

2.5.4 Sustainability

Sustainability has been proposed as a suitable disaster management paradigm (Asprone et al., 2014; Turner et al., 2003) for various reasons; primarily the need to consider broader

implications and interrelationships for the purpose of long-term community viability (Turner et al., 2003). Detailed discussion on sustainability in DOM is offered in section 5.0.

2.5.5 Disaster Vulnerability

Disaster vulnerability is a comprehensive paradigm, which emphasizes addressing the various liabilities that may exist in the physical, social, organizational or technical fabric of the community (McEntire et al., 2002). However, the rhetoric amongst policy makers (e.g. US federal agencies) has shifted from vulnerability to resilience; “there has been a noticeable shift in the rhetoric about hazards, moving from disaster vulnerability to disaster resilience, the latter viewed as a more proactive and positive expression of community engagement with natural hazard reduction (Cutter et al., 2008, p. 598). Conceptual linkages exist between vulnerability and resilience, but the debate is not settled, and we do not address those issues in this dissertation.

3.0 HUMANITARIAN OPERATIONS AND SUPPLY CHAIN MANAGEMENT

3.1 Introduction

The ascendant disaster operations research perspective in the operations management field has been that of the humanitarian organization (HO) as the decision maker, referred to in the literature as humanitarian operations; this trend is amply evidenced by research published in the top Operations Management (OM) journals (such as POM and JOM). As a consequence, the disaster operations literature has typically focused on addressing problems specific to the humanitarian paradigm.

Fundamentally, there are two types of humanitarian disaster operations. The first is Humanitarian Relief Operations (HRO), in which the humanitarian organization carries out activities to alleviate the suffering its beneficiary might experience, while under duress, during,

and right after the disaster event (Falasca, 2009; Starr & Van Wassenhove, 2011). The second consists of Humanitarian Development Operations (HDO), in which the humanitarian organization carries out activities that emphasize the long-term viability of the community (“building better”) post-event (Falasca, 2009; Starr & Van Wassenhove, 2011).

In the humanitarian operations paradigm, the HO is the decision maker and understandably this paradigm positions power in the hands of the donor (provider of the ‘capital’) and not the beneficiary. As a result, the community’s input is considered secondary. This case holds true when the beneficiary is under duress right before, during and right after the event. However, once relief work gives way to development work, in reality the power dynamic adjusts. This is evident in community-led disaster recovery and subsequent disaster mitigation planning; the community gets involved and is part of the process. Moreover, the community also provides some of the ‘capital’ to develop better and to be better prepared for the next disaster eventuality.

A primary result of the humanitarian organization paradigm is that a significant voice is lacking in this discussion – the affected community – critical to the sustainability of development-oriented programs (Kreistchmer et al., 2014; Polman, 2010). Moreover, there are significant ethical issues that arise when power is in the hands of the donor and not the affected community (Polman, 2010). Consequently, there is a critical need for the OM field to consider how techniques and methodologies in our field can have a wider influence beyond the humanitarian organization. Starr and Van Wassenhove (2014) note that the humanitarian operations field is dynamic and that “profound changes are expected in the future;”, in particular, they highlight the importance of expanding the nature of the humanitarian operations domain.

3.2 Humanitarian Supply Chains

In general the supply chain, whether in the conventional commercial context or the third sector context, refers to a series of related processes involved in the flow of goods or services from the supplier(s) to consumer(s) (Kleindorfer, Singhal & Van Wassenhove, 2005). In addition, a supply chain also includes the flow of both information and finance (Kleindorfer & Van Wassenhove, 2004; Van Wassenhove, 2006). These flows are not necessarily unidirectional. Specifically, a humanitarian supply chain is defined as the “process of planning, implementing and controlling the efficient, cost effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people” (Falasca, 2009, p. 13).

The adaptation of supply chain management principles to humanitarian applications is a significant though recent academic endeavor (Tomasini & Van Wassenhove, 2009; Van Wassenhove, 2006). While early scholars attempted to solve humanitarian problems using traditional supply chain techniques, the humanitarian context is primarily different (Starr & Van Wassenhove, 2014). Moreover, Holguin-Veras et al. (2012) show in their work that this context is dynamic, changing temporally with the disaster phase.

Several components make up supply chain management, including: procurement, operations, logistics and customer management (Kleindorfer et al., 2005). In the humanitarian supply chain context, the customer is the beneficiary; however, the beneficiary does not have the power the customer in the commercial context has.

3.3 Relationships in the Humanitarian Supply Chain

The relationships in supply chains for humanitarian operations can be quite complex, with a wide range of actors, type of relationships, and the various flows that exist between such relationships.

Based on Falasca (2009) and the following academic papers (Russell, 2005; Gatignon, Van Wassenhove & Charles, 2010; Balcik, Beamon, Krejci, Muramatsu & Ramirez, 2010), Figure 2-3 provides a broad view of the humanitarian supply chain.

There are five major groups of actors, one more (government) than the list offered by Falasca (2009); these include: HO, Suppliers, Donors, Beneficiary, and Government. There are four types of flows between these humanitarian agents: Information, Financial, Product and Service (Kleindorfer et al., 2005).

Figure 2-3 provides an overview of the flows extant in the humanitarian supply chain. The five key agents involved in the supply chain are:

- (i) Suppliers: Type 1 suppliers are contracted by the HO to offer goods/services, which are then employed by the HO for purposes of serving the beneficiary. Type 2 suppliers are those, though typically contracted by the HO, offer goods/services at no cost for benevolence reasons.
- (ii) Donors: Type 1 donors, based on requests from the HO, offer either financial or material forms of donation. Type 2 donors, based on appeals and the news media, offer either financial or material forms of donation. Material convergence is largely a result of type 2 donors sending mostly unnecessary donations to the HO.
- (iii) HO: The HO can be an international organization with local chapters (like ICRC, World Vision) or they can have collaborations with local HO's. These collaborations can be defined before the disaster or are formed right after the disaster (though these latter collaborations generally tend to be transient).
- (iv) Beneficiary: The affected community is the beneficiary of the HO's service either via relief provision, capacity development, etc.

- (v) The local or national government is also involved in offering relief services but delegates some of this service to the HO. The government also provides some form of assistance and constraints to the functions carried out by the HO.

3.4 Comparisons between Commercial and Humanitarian Supply Chains

Under several supply chain characteristics, Tables 1a offer a comparison between commercial and humanitarian relief supply chains. The comparison offered below is a summary of the work contained in the following papers: Apte (2010), Beamon (2004), Beamon and Balcik (2008), Davidson (2006), Falasca (2009), and Holguin-Veras et al. (2012).

Humanitarian supply chains that are geared towards long-term community development have more similarities with commercial supply chains. However, the primary difference lies in the fact that though the donor still has the power, the beneficiary also has its own form. Table 2-2a offers a comparison between humanitarian and commercial supply chains.

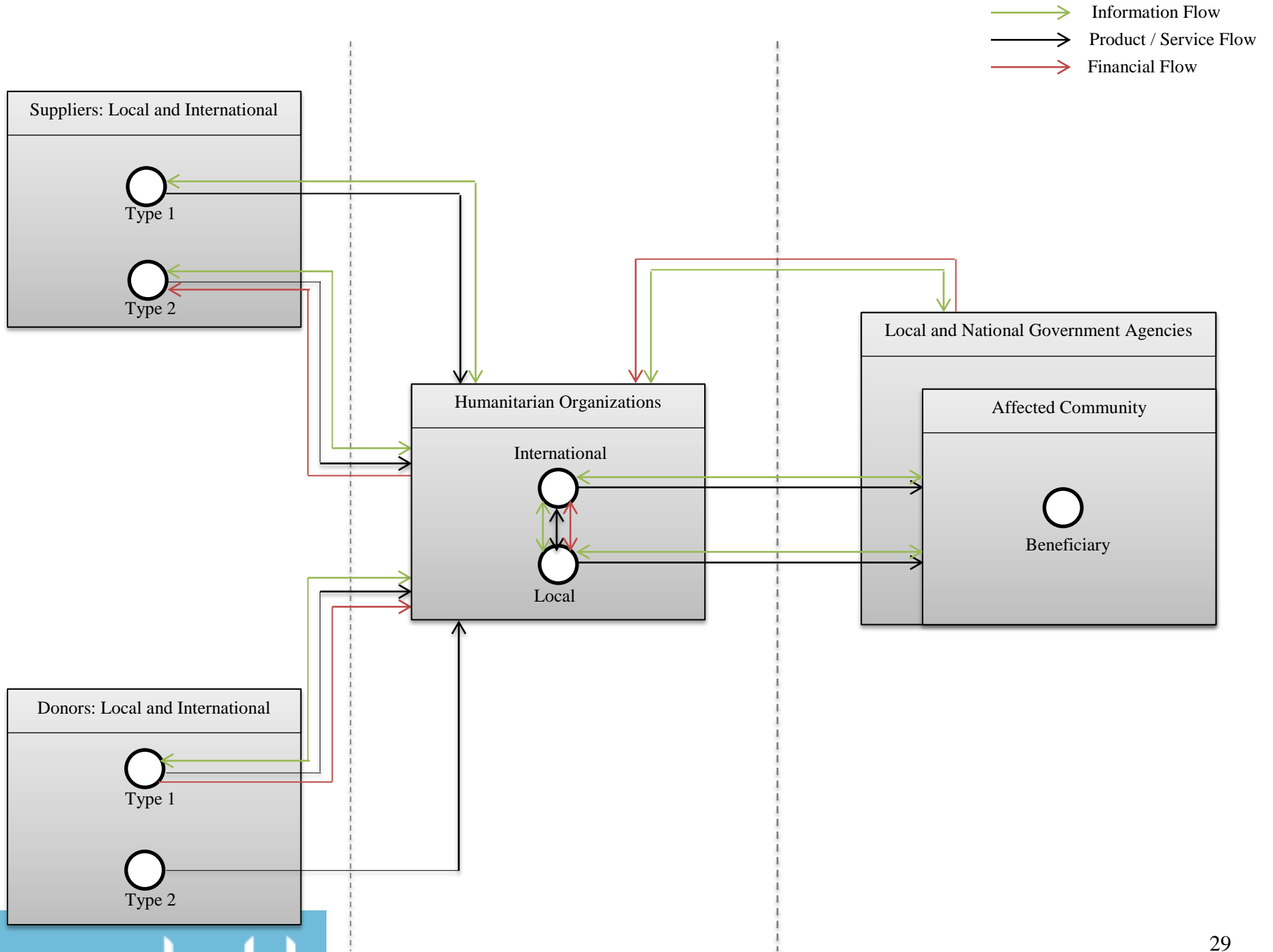


Figure 2-3. Humanitarian Supply Chain

Table 2-2 a. Comparison between Humanitarian Supply Chains and Commercial Supply Chains

Supply Chain Characteristic	Commercial Supply Chains	Humanitarian Relief Supply Chains
Decision Making Context		
a. Decision Maker	Commercial Firm	HO; with power primarily resting with the donor
b. Structure	Well-established, standard procedures, clear roles, generally centralized.	Decentralized, standard procedures exist dependent on the country. For example, the US implements the national incident management system.
c. Context	Stable	Highly dynamic
d. Decision Horizon	Permanent and continuous with operational, tactical and strategic plans.	Transient; Short-term
e. Collaboration issues	Stable, fixed.	Many actors, with limited collaboration due to the confusing and dynamic nature of the disaster event.
f. Social state of agent	Stable	Distressed
g. State of supporting systems, e.g. lifelines	Stable; In working condition	Uncertain
Performance Measure		
a. General Paradigm	Resource Performance, e.g. efficiency, cost	Output performance, e.g. coverage of needs, equity
b. Objective Pursued	Minimize costs e.g. inventory costs, transportation costs, etc.	Minimize deprivation costs, social costs. Logistic costs are secondary
Demand Issues		
a. Knowledge of demand	Demand is known	Demand is unknown
b. Periodicity and patterns	Stable	High uncertainty. Demand peaks right after the disaster and tapers off.
Logistics (Transportation)		
a. Route Certainty	Known & stable	Unknown & uncertain – issues of route disruptions
b. Carrier Certainty	Known & stable	Uncertain, especially if HO does not have local presence.
c. Inventory	Stable	Uncertain with high stock-out costs
d. Last mile distribution	Relatively simple, given existing distribution networks	Complicated; local distribution networks need to be formed
h. Structure	Static	Flexible; Dependent on need and location.
Supply Side Issues		
a. Price Gouging	Minimal; supplier contracts signed before hand	Significant; due to demand urgency.
b. Adverse selection	Minimal; penalties on product quality inserted in contracts. Firms have advanced quality assurance systems in place.	Significant; HO does not have time to carry out quality assurance; sometimes the goods go directly from supplier to the local HO distribution point.
c. Supplier selection	Stable	Sense of adhocness
d. Material Convergence	Non-existent	Severe problem

Financial Supply Chain		
a. Financial Flow	Customer → Company→Shareholders	Donor→HO → Beneficiary
b. Flow Certainty	Stable; dependent on customer demand	Limited, unreliable; dependent on unreliable donations. Limitations can be placed on donations by the donor via earmarking.
Information Supply Chain		
a. Information Systems	Well-established with standardized protocols	Lack of well-developed protocols
b. Information availability	Dependent on systems installed	Scarce; much of the data is unstructured
Employee Management		
a. Workforce Stability	Stable	Volunteers are transient
b. Workforce Periodicity	Steady workforce governed by operations requirements	Volunteer convergence; peaks right after media coverage and right after the disaster event, tapers off with time.
c. Workforce Structure	Well-established and standardized procedures; clear job roles	Job roles are dynamic

Table 2-2 b. Comparison between Humanitarian Relief and Humanitarian Development Supply Chains

Supply Chain Characteristic	Humanitarian Relief Supply Chains	Humanitarian Development Supply Chains
Who has the power?	HO; with power primarily resting with the donor.	HO; with power shared with the beneficiary (affected community). The beneficiary provides resources and input towards achieving desired long-term outcomes.
Decision Horizon	Transient; short-term.	Transient; but longer-term.
Collaboration	Many actors, with limited collaboration due to the confusing and dynamic nature of the disaster event.	Collaboration is clearer. Some HO's move out once relief work is over. The government and the beneficiary take a more involved role.
Objective Pursued	Minimize deprivation costs, social costs; logistic costs are secondary.	Minimize costs, e.g., logistic costs Maximize beneficiary benefit
Demand Issues	Demand is uncertain; peaks right after the disaster and tapers off	Mostly known and mostly stable
Supply Side Issues	Risk of price gouging and adverse selection (HO does not have time/resources to carry out quality assurance) is significant	Minimal risk, as demand is stable and HO's have more time to ensure quality of supply.
Material Convergence	Severe problem	Less severe; unused items returned, recycled or discarded
Volunteer Convergence	Severe problem; all the volunteers have to be managed. Liability and safety issues exist	Less severe

3.5 Extending the Emphasis from Humanitarian Logistics to Humanitarian Supply Chains

Van Wassenhove (2006) highlights that 80% of humanitarian relief work is logistics; it is no surprise that much of the current research in humanitarian operations focuses on logistics. However there is a need to extend this perspective to include the entire supply chain perspective. If research is expanded to include more upstream issues (such as a network of suppliers), critical costs may be addressed. In the commercial context the lack of a product suffers acceptable penalties, but not so in humanitarian logistics where one may lose a life.

Moreover, humanitarian logistics concerns itself primarily with the movement, storage and final delivery of humanitarian relief goods from donors to beneficiaries (Van Wassenhove, 2006; Thomas & Kopczak, 2005). The formal definitions offered for humanitarian logistics include (note the emphasis in the definitions on product flow):

“Process of planning, implementing and controlling the efficient, cost-effective flow of and storage of goods and materials as well as related information, from point of origin to point of consumption for the purpose of meeting the end beneficiary’s requirement.” (Thomas & Mizushima, 2005, p. 60)

*“...getting the **right goods** to the right place and distributed to the right people at the right time.” (Van Wassenhove, 2006, p. 477)*

Much of the humanitarian operations work emphasizes the product flow even though the main purpose of the HO is **relief service**. The HO provides delivery of critical goods and disaster response services to the beneficiary as part of relief service delivery. There is much promise for the field of service operations in humanitarian operations. However, there is a caveat; much of the service side of OM research is driven by the fact that customers have power.

3.6 Supply Chain Relationships and Behavioral Research

As highlighted in Figure 2-3, there are several relationships between the various humanitarian supply chain agents. To study these relationships, this paper employs the agency relationship (principal – agent) to distinguish between the actor (principal) who delegates work and the actor (agent) who performs it on the principal's behalf (Eisenhardt, 1989; Sharma, 1997). In this regard, there are three types of relationships that exist between the agency and the principal in their roles: Information, Power, and Knowledge.

Table 2-3. Humanitarian Supply Chain Relationships

Relationship		Description	Opportunism/Issues Based on Type of Relationship	Controls
Principal	Agent			
HO	Supplier	HO contracts out supply and delivery of goods and services to required delivery points.	1. Power Asymmetry: Supplier can dictate the prices due to the emergency and the resulting urgency in demand (Price Gouging). (Husted, 2007).	Price gouging affects the public's perception of the firm. (Hemphill, 2009) (Tsalikis & Seaton, 2006). This is because, in terms of equity, it is seen as unfair (Snyder, 2009), though it results in efficient allocation of scarce resources (Zwolinski, 2008).
			2. Information Asymmetry: May exist due to adverse selection. The HO does not have sufficient time to ensure quality of incoming goods; it accepts the delivery based on trust.	By establishing supply-side contracts before the emergency event, HO's can have quality penalties included in their contracts.
Donor	HO	Donors are non-experts, and prefer to have experts responding to disasters; leaving professionals to handle the relief work. Donors provide both financial and material support to humanitarian organizations, under specified accountability directives, which enables HO's to act on their humanitarian prerogative.	1. Power Asymmetry: The donors have the power and sometimes ' earmark ' their donations.	
			2. Knowledge Asymmetry: The HO's are the experts and by virtue of their knowledge the HO has power over the donor.	1. Self-interest: the HO is driven by a multiplicity of motives including altruism, and a commitment to serve the public (Sharma, 1997) 2. Community control: Belonging to an umbrella body of other HO's can provide some sort of control (Sharma, 1997).
			3. Information Asymmetry: The HO is accountable to the donor; however the HO controls the information flow regarding relief work.	Rating Agencies: Charity Navigator

HO	HO	Alliances	Knowledge Asymmetry: The local HO has local knowledge and existing networks with the government, in terms of volunteers, distribution networks, etc.	Establishment of local chapter
			Information Asymmetry: The local HO carries out activities on behalf of the international HO, and can sometimes mislead the principal HO.	
Government	HO	The government delegates its role to the HO.	Power Asymmetry: Government makes the rules and the contracts. Governments restrict HO independence; sometimes compelling agencies to act in ways counter to the HO's interest (Behrer, 2011).	
			Knowledge Asymmetry: HO's are the experts on relief service delivery, and by virtue of their knowledge, the HO has power over the government.	
			Information Asymmetry: Sometimes the government does not know what is happening. Relief agencies take unilateral action	

4.0 DISASTER RESILIENCE

The adoption and rapid expansion of the resilience concept outside the physical sciences is due to Holling's (1973) seminal work in ecology. Yet resilience is a fiercely contested concept with rich historical disciplinary traditions (Alexander, 2013; Norris, Stevens, B. Pfefferbaum, Wyche, & R. Pfefferbaum, 2008). There are more granular distinctions in the disaster literature and interested readers can see Alexander (2013), Norris et al. (2008), and Zhou, Wan, and Jia (2010) for a comprehensive discussion.

4.1 Disaster Resilience Models

Kathleen Tierney posits that there are three major frameworks in current literature that conceptualize resilience (Tierney, 2009). These are (1) Fran Norris' conceptualization of resilience as a set of networked adaptive capacities (Norris et al., 2008); (2) Bruneau's conceptualization of resilience as a process that has the following desired outcomes: reduced risk, reduced initial damage, and prompt recovery after a disaster (Bruneau et al., 2003); and (3) Adam Rose's resilience model (Rose, 2004), which is an offshoot of Bruneau et al.'s work, the difference lying in viewing resilience as a recovery process that does not include robustness. (Due to the similarity to Bruneau's model, this study does not discuss Rose's model separately). Tierney also refers to the social vulnerability indicator models of Cutter (Cutter, Boruff, & Shirley, 2003). Cutter extends this work to formulate a place-based resilience model which conceptualizes resilience as a dynamic process that captures the specificity of a location "characteristic" and that characteristic's contribution to resilience (Cutter et al., 2008). There are other resilience conceptualizations (for example, the panarchy framework by Gunderson & Holling 2001), but this dissertation focuses on those models emphasized by Tierney (2009). After brief descriptions of each of the models, a comparative evaluation is offered.

4.1.1 The 4 R model (Bruneau et al., 2003)

The name 4 R derives from the models definition of resilience using Robustness, Rapidity, Resourcefulness and Redundancy. This model initially proposed by Bruneau et al. in 2003 (Bruneau et al., 2003) and subsequently improved by Cimmellaro, Reinhorn, and Bruneau (2010) and Zobel (2010, 2011), has seen substantial use, mostly but not exclusively within engineering circles, due to its quantitative nature.

In the 4 R model, a resilient system results in the following outcomes, to some degree: i) reduced risk, ii) reduced initial impact of disaster, and iii) reduced time to complete recovery. The model further points out that the properties of resilience can be considered dual in nature, in the sense that there are: i). Outcomes of resilience: Rapidity (speed of complete recovery, captured by the abscissa of Figure 2-4) and Robustness (reduced risk and reduced initial impact, captured by the ordinate of Figure 2-4), as well as the ii). Means of resilience: Resourcefulness (community capacities that apply resources (physical, human, technological, etc.) to needs), and Redundancy (networkability and replaceability of resources to enable substitution in case of failure). An entity's resilience can then be described by resources (in the broadest terms possible) available, and how those resources are allocated – see parallels on resources with Norris's model below.

Bruneau et al. provide a mathematical formulation to quantify resilience that is very similar to materials science evaluations of the modulus of resilience (Callister & Rethwisch, 2012) and capacity utilization formulations. See Figure 2- 4.



$$R = \int_{t_0}^{t_1} [100 - Q(t)] dt$$

Figure 2-4. Conceptual Definition of Resilience Measure (R) (Bruneau et al., 2003)

The above formulation for resilience (R), where $Q(t)$ represents the quality of infrastructure at time t , **incorrectly** implies that a smaller loss results in a lower resilience. In other words, since the resilience measure refers to the area above the curve, a small disaster will result in larger resilience. Subsequent future work by Zobel and Cimellaro corrects this formulation. Zobel defines an entity's resilience measure as normalized area below the curve (Zobel, 2010); $R = \left(\int_{t_0}^{t_1} q(t) dt \right) / T^*$, so that $R \in [0,1]$.

The 4 R model also points to the four interrelated dimensions of resilience (multi-dimensionality of resilience) that can be categorized into two main categories: (i).The system performance criteria (including both “technical” and “organization” dimensions), and (ii).Measurable outcomes (incorporating “social” as well as “economic” considerations). The dimensions are interrelated in that social and economic measures are used in evaluating resilience. These measures are translated into desired actions by forming system performance criteria (technical and organizational).

In summary, to assess the correct measure for resilience, the 4 R model requires the following input factors: (i). Prior conditions (ii). Damage averted due to disaster management decisions, and (iii).Time it takes for recovery to get back to a state of “normalcy.”

4.1.2 Community resilience as networked adaptive capacities (Norris et al., 2008).

According to Norris et al, adaptive capacities are resources with dynamic attributes (attributes that change their state/value over time). Subsequently, resilience is defined as a process that

links a community's adaptive capacities to its outcome, which in this case is, adaptation to an extreme event.

The adaptive capacities are split among four competencies: economic development, social capital, information, and communication. Since these competencies have attributes that change over time, the model uses the 4 R model to ascribe specific dynamic attributes (robustness, rapidity, redundancy) to the adaptive capacities. For example, the resource economic development is characterized by three dynamic attributes – rapidity, robustness and redundancy (resourcefulness is not included in this description because it is viewed as a resource rather than a dynamic attribute).

In summary, the dynamic attributes of the resources (from start to end) and how well the system manages to use these resources to adapt to an extreme event are essential to the system's resilience.

4.1.3 Place-based model (Cutter et al., 2008)

The place-based model developed by Cutter et al. provides a framework in which disaster resilience at the community and geographical level can be assessed, based on location. The model conceptualizes resilience in a manner that enables the conversion of relevant spatial information into resilience measures, which in turn can be used for relative resilience comparisons with other communities.

Cutter's model views resilience as a dynamic process ("continual learning and adaptation"), which results in better community decision-making capacity to handle future hazards. However, the model does not measure resilience as a dynamic process.

In summary, the system's resilience is a result of the collective effect of the event characteristics (a negative effect); the community's current state (described by the community's

antecedent conditions - inherent resilience as well as inherent vulnerability); and coping responses (recovery actions). See parallels with the 4R model's input factors.

4.2 Model Comparisons

In summary, from the three models discussed above, Norris et al. (2008) describe resilience as a process, Bruneau et al. (2003)/Zobel (2010, 2011) describe resilience as a process with dynamic outcomes, and Cutter et al. (2008) describe resilience as an outcome.

A process is defined as a “network of activities performed by resources that transform inputs into outputs” (Wisner & Stanley, 2007). The definition consists of the following key components: inputs, outputs, a set of related activities that convert the inputs to outputs, and resources (system capacities) that enable these activities. See Figure 2-5.

The position this dissertation takes is: the dynamic attributes of the system's resources and capacities, and how well the system manages to use these resources, describe the system's resilience. Moreover, in managing these resources, the outcomes of the activities carried out by the system, can be measured over time. Accordingly, we use the Bruneau et al. (2003) conceptualization of resilience.

A comparative evaluation of the three models, under the context of a process, is offered in Table 2-4.

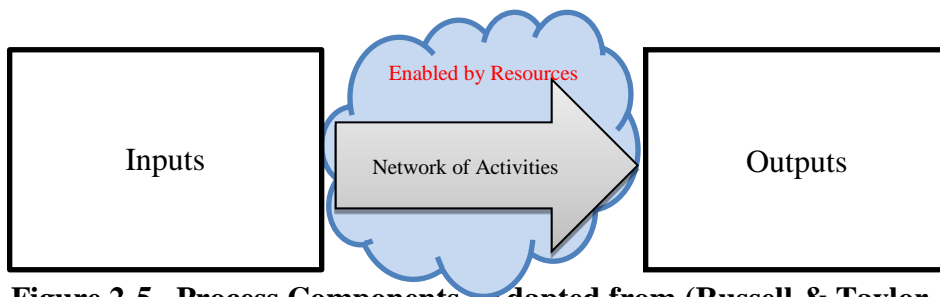


Figure 2-5. Process Components. Adapted from (Russell & Taylor, 2011; Wisner & Stanley, 2007)

Table 2-4. Comparison of Resilience Conceptualization Models

	Resilience Definition	Related Activities	Resources capacities
(Bruneau et al., 2003)	“ Ability of social units to mitigate hazards, contain the effects of disasters when they occur and carry out recovery activities in ways that minimize social disruption ”	Disaster management actions	Resources: 1. Physical: Technological, Organizational 2. Community: Social Economic Capacities: 1. Resourcefulness: Community capacities that apply resources to need 2. Redundancy: Networkability and replaceability of resources to enable substitution in case of failure.
(Cutter et al., 2008)	“Ability of social system to respond and recover from disaster and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the social system to re-organize, change, and learn in response to a threat.”	1. Mitigation 2. Preparedness 3. Response 4. Recovery	Adaptive Resilience 1. Social Learning 2. Improvisation
(Norris et al., 2008)	” Community resilience is a process linking a network of adaptive capacities to adaptation after a disturbance or adversity”	1. Networking and connecting adaptive capacities 2. Applying capacities to the process of learning and adapting to disaster	Adaptive Capacities 1. Economic Development 2. Social Capital 3. Community Competence 4. Information and Communication

5.0 SUSTAINABILITY AND DOM

The inherent linkage between disasters and sustainability is premised on the idea that disasters are a threat to the long-term viability of a community (Dovers, 2004). In lieu of staggering disaster-related losses, the short-term focus of disaster policies, and the lack of emphasis on systems and linkages beyond the immediate disaster and affected entity, Godschalk, Kaiser and Berke (1998), Mileti (1999), and Turner et al. (2003) advocated the need for a different paradigm to disaster management, i.e., the sustainability paradigm.

5.1 Definition

The concept of sustainable development, as first concisely articulated by the World Commission on Environment and Development (WCED), was a vision of ecological concern, inter-generational equity, and economic development (National Research Council [NRC], 2006). The WCED's definition of sustainable development, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43), has since been adapted for DM. In addition, Mileti's seminal work in this area defined sustainable disaster management, in particular mitigation, as the capacity of a community to manage the effects of a disaster without significant external help (Mileti, 1999). These two definitions have been the premise of all other conceptualizations in this area (McEntire, 2005).

Sustainability broadens and refocuses DOM to include the interdependence of environment, human, and economic development domains; and the operationalization by various mechanisms of diverse functional and spatio-temporal scales for the purpose of long-term community viability and stability.

5.2 Critiques and Responses

The sustainability paradigm has contributed significantly to disaster research, particularly because it emphasizes a community-driven DM process; it adds to the understanding of the link between actions (particularly those of development – mitigation and long term recovery) and disasters; and it emphasizes long-term viability. However, it is not without its criticisms. This paper addresses the three most common criticisms.

5.2.1 Community Engagement

Aguierre (2002) raises the complexity with spatial and social scales in relation to community engagement, highlighting the difficulty of building consensus and connecting decisions at the local level with the more bureaucratic global processes. Aguirre, responding to Mileti's work on sustainable mitigation, argues that it offers an expurgated version of sustainability – devoid of all the difficulties that arise with actual implementation. Critically, to this paper, the underlying concern for Aguirre, outside of operationalizing community engagement, is its validity: how does community engagement make the decision-making system more effective?

Nevertheless, the [U.S.] National Research Council (NRC) (2006) highlights the fact that local issues are inevitably linked to global ones, even if making those connections are difficult. Moreover, central to the concern of validity, Pearce (2003), emphasizing the importance of engagement in effective decision-making, argues that first, the inclusion of the local community increases the chances of finding reasonable, applicable, and local solutions. Second she argues, this inclusion allows the disadvantaged a voice in ensuring equity. Furthermore, Pearce (2003, Ch. 4) offers practical steps to operationalizing the link between the local and global.

A similar critique, which goes along with issues of community engagement, is in reference to exploitations possible in a consensual model of politics. Aguirre (2002) argues that engagement schemes may not function as planned, particularly because the process is open to

manipulation, consistent with public evidence (Aguierre, 2002). While issues of patronage and clientelism still persist in political realities, the argument that one must not implement a process because it is open to exploitation is antediluvian. By that logic, “we should get rid of hospitals because sometimes they make mistakes” (Dilbert, Feb. 23, 2014).

5.2.2 Cultural Change

A second critique also by Aguirre (2002), aimed at Mileti’s (1999) emphasis on the need for a cultural change, highlighted its impracticality. Mileti (1999) emphasized the need to change several US cultural mechanisms, including individualism and the short-term profit making mindset, in order to enable sustainability in disaster management. However, Aguirre argued that bringing about massive cultural change is extremely difficult and moreover, is not the purview of disaster research. (NRC) (2006) addresses these issues and discusses practical ways in which cultural change can be induced. In retrospect, at the present time in 2014, cultural change is occurring, exemplified particularly among the younger generations who emphasize sustainable living. This is also evidenced by the statistic that 91% of global consumers would change an original brand, given similar quality and price, to brands associated with a good cause, e.g. environmental protection, resource conservation, etc. (Cone Communications, 2013).

5.2.3 Temporal and Systemic Exclusivity

The final critique is the temporal and systemic exclusivity inherent in the sustainability paradigm (Aguierre, 2002; Berke, 1995; McEntire, 2005; McEntire et al., 2002). In particular, McEntire and Aguirre argue that the sustainability paradigm excludes short-term relief activities – preparedness, response and short-term recovery, for the sake of long-term development type activities such as mitigation and long-term recovery. Consequently, both McEntire and Aguirre posit that sustainability as a paradigm fails to capture the entire process of DOM.

This critique motivates Chapter 3's discussion on creating an integrative planning framework for sustainable DOM, which addresses the tension between long-term viability and disaster relief focused operations.

6.0 DOM PLANNING

Disaster planning at its essence is the development of a strategy by various community stakeholders for the purpose of limiting the future impact of disasters and recovering back to a state of normalcy (Dynes, Quarantelli and Kreps, 1972; Godschalk et al., 1998; Waeckerle, 1991; Kartez & Lindell, 1987).

There are various issues in planning from coordination, risk evaluation, relief-operations, to development operations. In this dissertation we focus particularly on development operations. In this context, we define disaster operations management planning as a process by which various community stakeholders specify appropriate action (activity) levels given specific objectives and limited resources (human, supplies, equipment), over specific time horizons, as they attempt to limit the future impact of disasters and recover back to a state of normalcy.

6.1 Stakeholders

By stakeholders, this dissertation refers to the affected community, emergency professionals, government (local and national), HO's, faith based organizations, civil society, and NGO's.

Historically, disaster management had been 'for the people' rather than 'with the people,' resulting in an unsuccessful and inefficient process (Berke et al., 1993, Pearce, 2003). The primary risk of community exclusion in the disaster planning process – both then and now, as highlighted in the disaster literature, was/is the underdevelopment of local community capacities for subsequent disaster(s) (Berke et al., 1993, Pearce, 2003). However by the late 1970's, with changes in the legislative language that emphasized public participation, a more educated and

informed populace became significantly more interested in having a say on the decisions that affected it (Thomas, 1995). It is now recognized that the inclusion of the affected community is fundamental to the disaster planning process. For comprehensive guides to operationalizing community inclusion in planning see Thomas (1995), and Thomas (2012); as applied to DOM, see Pearce (2003).

Critical to the discussion of this paper is the matter of which specific DOM planning issues need community acceptance, as not all of them do (Godschalk, Kaiser, & Berke, 1998; Thomas, 1993, 2012). Thomas (1995, 2012) indicates that in situations where the planning decision is highly technical in nature, public participation would not be effective; however, in situations where public acceptance is fundamental to successful implementation, one should consider how to embrace community engagement. In particular, both Berke et al. (1993) and Pearce (2003), recommend the inclusion of the affected community *when discussing issues of goals* (objectives). Making the same point, the National Research Council (NRC) (2006) concludes that stakeholder inclusion provides a fundamental mechanism in which the affected community can ascribe varying levels of value across competing objectives.

6.2 Objectives

The objectives represent any value(s) of import to the community, e.g., infrastructure worth, racial and generational equity, economic development, propensity to be ecologically responsible, the tendency to “bounce back” quickly, etc. Moreover, since this paper is focused on long-term planning, this study stipulates a planning horizon and then emphasizes the performance of the community values over the entire planning horizon.

6.3 Activities

Since our planning model is focused on development, the DOM activities considered are those that potentially meet the goals of the mitigation and long-term recovery phases. Depending on the objectives defined, these activities can include construction of seawalls, floodplain buy-back, etc.

6.4 Resources

These constitute the limited assets (physical, human, etc.) that stakeholders have access to, which have to be shared across all selected activities, irrespective of disaster management phases.

7.0 THE MULTI-HAZARD CONTEXT

Many regions in the world today experience and are vulnerable to several hazards (Kappes, Keiler, Elverfeldt, & Glade, 2012). For example, an urban city center such as San Francisco, CA with a population close to 850,000 is at risk from wild fires, tsunamis, landslides, earthquakes, flooding, heat waves, and droughts (Ayyub, 2013). This reality necessitates a multi-hazard approach to disaster planning and management. It is widely recognized, in such regions, that traditional disaster management motivated by a single disaster in isolation is not only inadequate, but inefficient (Scawthorn et al., 2006). This inadequacy is prominent particularly given the context of climate change and the increased frequency of weather extremes over the coming decades (Lung, Lavalle, Hiederer, Dosio & Bouwer, 2013). The recognition of the need for an inclusive and comprehensive disaster planning model has motivated institutions like FEMA (FEMA, 1995) and the UN (UN-ISDR, 2005) to recommend the use of a multi-hazard approach to risk analysis and assessment.

7.1 Background on Multi-Hazard Management

A brief survey on multi-hazard management including its history, benefits, and concerns is provided in this section.

7.1.1 History of Multi-Hazard Management in the USA

The multi-hazard approach in the US was initially highlighted as a means of accounting for the various types of disaster risks that a certain region may face, aptly coined 'All-Hazards.' The term 'All-Hazards' is commonly misunderstood to involve all types of possible hazards rather than 'likely hazards' Waugh (2005) - for example, in the US, at the national level, 15 such scenarios have been defined. The underlying motivation behind the All-Hazards approach, given commonality among hazards, is the development of standardized procedures that can be applied to a wide range of most likely events (Bigley & Roberts, 2001). This paradigm has, in fact, evolved over time and is now institutionalized in the national incident management system (NIMS) and the national response framework that the US employs (Hemond & Robert, 2012). Practically, this means that a standardized operating procedure, with specific action steps, is to be applied whether the disaster is due to Superstorm Sandy, internal unrest, or an external terrorist attack (Caruson & MacManus, 2011; Congress, 2007).

7.1.2 Benefits

Significant benefits can be achieved by taking a multi-hazard perspective. (i) Economic and outcome efficiencies can be gained during the planning process (Pollet, 2009). For example, the consideration of dependencies may yield a better package of intervention strategies that secure a region or critical asset, against a wider range of hazards. Moreover, in an increasingly resource-constrained environment, the emphasis on effective use of resources results in the selection and implementation of intervention strategies that can secure additional vulnerabilities (Chacko, Rees, & Zobel, 2014; Caruson & MacManus, 2011; Peterson & Truver, 2006; Waugh & Tierney, 2007). For example, the US Coast Guard has to contend with risks associated with about 95,000 miles of navigable waterways. Through implementation of the multi-hazards approach, the

Coast Guard has been able to support more cooperative missions – using their resources to help in natural hazard management (Hurricane Katrina), drug trafficking, and protection of the US coasts (Peterson & Truver, 2006). (ii) Better and more accurate risk assessments that then result in apposite disaster planning decisions (Cox, 2009; Marzocchi, Garcia-Aristizabal, Mastellone, & Di Ruocco, 2012; Selva, 2013).

In summary, the benefits provide the potential for significant collaboration and resource sharing across agencies, even those outside the jurisdiction of the ‘provider’ agency itself (Caruson & MacManus, 2011; Waugh & Tierney, 2007), better hazards preparedness (Caruson & MacManus, 2011; FEMA, 2007; Hoard et al., 2005; Hodge, Gostin, & Vernick, 2007), and sustainability/continuity of mission (Hoard et al., 2005).

7.1.3 Possible concerns

Concerns arising out of discussions and applications of the multi-hazard approach tend to specifically focus on the information required. These concerns can be generalized into two categories:

(i) *Biased information*: Information required in multi-hazard analysis include data on the commonalities that exist between several hazard vulnerabilities, and the region/assets under consideration. Since these assessments invariably determine prioritization in resource allocation, the outcome of biased assessments can be contentious. Bias in these assessments can be generalized in two forms: (1) Decision makers tend to assign spatial assets (location and built environment) with a wider range of hazards than social assets (e.g., community wellness, etc.) (Caruson & MacManus, 2011). This bias arises because of the inherent difficulty in assessing abstract constructs. (2) Decision makers may not correctly assess hazard convergence, particularly in cases where there doesn’t exist a high degree of it. In particular, there is concern

amongst academicians and practitioners that some disasters are so different from each other that it is pointless attempting to provide a similar plan for both hazards (Waugh, 2004; Altay & Ramirez, 2010). An example case cited to support ‘commonality deficiency’ was that between bioterrorism and natural hazards (Waugh, 2004). However, on the contrary, recent work by Ayyub (2013) highlights that while some specific disasters may lack commonality, on the whole there are a considerable number of cases where commonality exists.

(ii) *Information deficiency*: The kind of information required to conduct an accurate commonality assessment requires the synthesis of geographic, social, economic, ecological, and infrastructural elements (Caruson & MacManus, 2011; Waugh & Tierney, 2007). Unfortunately, the development of appropriate data sets and structures in the literature and in practice are limited.

7.1.4 Discussion themes

The qualitative discussion in this area can be summarized into two broad categories: Spatial and nature of hazard.

Spatial refers to the space component of the discussion, either in terms of a region or in terms of critical assets that are important in a region or state.

- (i) **Regional, Multi-hazard**: The emphasis is on hazards that are prone to a specific region (Greiving, 2006; Hewitt and Burton, 1971).
- (ii) **Critical Asset, Multi-hazard**: The emphasis is on specific critical assets, which are important to a state/region, and the hazards that might affect them (Dillon et al., 2009).

Nature of hazard refers to the type of multi-hazard that is considered.

- (i) All-Hazards: The consideration of likely hazards that may occur, with the emphasis on seeking the commonalities that exist in likely hazards and using that information and sets of relationships to plan better (Waugh, 2005).
- (ii) Secondary Hazards: The consideration of the epiphenomenal nature of a hazard, also described in some literature as more-than-one hazard (Fiedrich, Gehbauer, & Rickers, 2000; Zhang, Li, & Liu, 2012; Selva, 2013; Marzocchi et al., 2012; Kappes et al., 2012).
- (iii) The possible interaction between independent hazards, which happen to occur simultaneously (Pollet, 2009; Selva, 2013; Marzocchi et al., 2012).

7.2 Mono-Hazard vs. Multi-Hazard

The consideration of a single hazard in isolation, either single event or multi-event, is a motivation this dissertation refers to as mono-hazard. By multi-hazard, this dissertation refers to the consideration of an entire range of likely hazards. For example, modeling the expected occurrence of five flood disaster events is referred to as mono-hazard; conversely, the consideration of a flood event and an earthquake event is referred to as multi-hazard. In this section we compare modeling considerations between mono-hazard and a multi-hazards approach.

Using Figure 2-2, which highlights the basic elements involved in disaster management, this section evaluates the impact on the relationships highlighted in section 2.3. How does the consideration of multiple hazards affect the relationships listed? Moreover, what additional considerations need to be accounted for when modeling disaster management under a multi-hazards context?

In a multi-hazards context, one would naturally expect that any variations between mono-hazard and multi-hazard models are specifically amongst the relationships where the hazard is

incorporated, as highlighted (in red) in table 5. However, due to dependencies that exist between disaster management elements, there may be more relationships to consider. Moreover, the consideration of multiple hazards implies the consideration of more intervention strategies to counter these hazards, and the inclusion of more assets that may come under the threat of these hazards. This increases the likelihood of an underlying dependency. These dependency relationships can provide some benefit - in the multi-hazard context, efficiencies can be obtained by taking advantage of the synergies that exist in the dependency relationships (Pollet, 2009). In particular, the literature notes two specific efficiencies that can be obtained: the implementation of a portfolio of intervention strategies that result in additional synergistic benefits, and the use of a single resource to support multiple intervention strategies (Chacko et al., 2014; Caruson & MacManus, 2011).

Table 5 provides a comparison between mono-hazard and multi-hazard models against a list of possible relationships between disaster management elements.

Table 2-5. Comparison Between Relationships in a Mono-Hazard and Multi-Hazard Models

Relationships	Mono-Hazard	Multi-Hazard
<i>Relationships Within Elements</i>		
Hazard – Hazard (H-H)	Not considered, there is only one hazard	One disaster may spawn another; multiple disasters may occur simultaneously; one disaster may make an asset/region more vulnerable to the next one.
Critical Asset – Critical Asset (C-C)	Dependencies between critical assets or regions. For example, failure dependencies.	Dependencies between critical assets or regions. For example, failure dependencies.
Strategy – Strategy (S-S)	Dependencies exist between intervention strategies. These dependencies may be either positive or negative. For example, building levees may reduce region A’s impact, but nearby region B may end up having a worse impact.	Dependencies exist between intervention strategies. These dependencies may be either positive or negative. For example, building levees may reduce region A’s impact, but nearby region B may end up having a worse impact.
Resource – Resource (R-R)	Dependencies between resources or capacities. For example, failure dependencies.	Dependencies between resources or capacities. For example, failure dependencies.
<i>Interaction Relationships Between Elements</i>		
Strategy – Critical Asset (S-C)	Intervention strategy secures one or multiple assets	Intervention strategy secures one or multiple assets
Strategy – Available Resources (S-R)	Intervention strategy secures one or multiple resources	Intervention strategy secures one or multiple resources
Strategy – Hazard (S-H)	Intervention strategy geared towards securing one hazard vulnerability	Intervention strategy secures multiple hazard vulnerabilities.
Hazard – Critical Asset, Resources (H-C / H-R)	A single hazard’s impact may affect a single or multiple asset/region and resource(s)	Hazards and their interactions (see H-H) affects single or multiple assets/regions and resource(s)
Resource – Strategy (R-S)	Application of a resource supports one or multiple intervention strategies	Application of a resource supports one or multiple intervention strategies

7.4 Limitations with Current Analytical Multi-Hazard Models

Analytical models that consider the multi-hazard context are relatively new. Some of the first models that considered multiple hazards were in actual fact multi-event models, in that they considered the same hazard occurring multiple times over a specific duration (e.g. Barbarosoglu & Arda, 2004). The multi-event contribution to this area of research is critical as it offers an extension from the short-term single incident, to the realistic consideration of several incidents over a decision horizon. However, the single hazard perspective fails to consider the entire range of risks that a community or system faces (Kappes et al., 2012).

A summary of the features in a sample of analytical multi-hazard models is provided in Table 2-6. However, the three key limitations in typical analytical models can be summarized into three issues:

- (i) Typical MH models limit their models to additive effects of disasters (see Zhuang and Bier (2007); Zhang et al., (2012) Canto-Perello, Curiel-Esparza, and Calvo (2013) etc.), failing to consider the dependencies that exist when considering multiple hazards and their interactions, in addition to the additive effects (Kappes et al., 2012).
- (ii) The traditional MH models limit their scope and exclude the additional interactions between strategies, resources etc. (Chacko, et al., 2014; Kappes et al., 2012)
- (iii) Finally, the traditional multi-hazard paradigm is that of risk reduction (pre-event). It is for this reason, that most analytical models are focused on risk assessment and ranking (see Table 2-6).

More critically, there are no models that consider the complete disaster management cycle, both pre-disaster and post-disaster actions (e.g. long-term recovery). Modeling

both of these together is essential to breaking the disaster cycle of damage, reconstruction, and repeated damage.

Table 2-6. Analytical MH Models

Disaster Management Phases	Methodologies					Technical features relevant to Multi Hazard						Performance Measures						
	Game Theoretic Approaches	Risk Assessment and Ranking	Cost – Benefit Analysis	Optimization	Other	H-H	C-C	S-S	R-R	S-C	S-R	S-H	H-C / H-R	R-S	Economic Cost	Social Cost Proxy	Time	Other
Primary consideration: Pre-disaster actions																		
Abkowitz & Chatterjee (2012)		✓											✓		✓	*		
Ayyub et al (2007)			✓				✓						✓		✓	✓	✓	✓
Canto-Perello et al (2013)		✓													✓	✓		
Chacko, Rees & Zobel (2014)					✓			✓					✓	✓				✓
Chatterjee & Abkowitz (2011)		✓											✓		✓	*		
Dillon et al (2009)		✓						✓		✓			✓		✓	✓		✓
Hausken et al (2009)	✓											✓			✓			
Li et al (2009)		✓				✓	✓						✓		✓	✓		
Marzochhi et al (2012)		✓			✓	✓									✓	✓		
Selva et al (2013)		✓			✓	✓									✓			
Stewart & Mueller (2014)			✓					✓							✓			
Zhang et al.(2012)					✓													✓
Zhuang & Bier (2007)	✓														✓			
Primary considerations: Post- disaster actions																		
None																		
Primary considerations: Both pre and post disaster actions																		
None																		

* Human casualty and other social costs are converted to a dollar value and represented as an economic cost

8.0 METHODOLOGIES

8.1 Decision Support Systems

Decision Support Systems (DSS) are defined as computer based information systems that use models and data to provide useful information so as to aid the decision maker in making semi-structured decisions (Sprague & Carlson, 1982). A semi-structured decision is a decision that is neither completely structured nor completely unstructured, where a structured decision is one for which solution steps (i.e., an algorithm) can be clearly formulated. The rationale for DSS, as a natural evolution from Electronic Data Processing (EDP) and Management Information Systems (MIS), was the increased need by managers for system support that would aid in decision making. In fact, the first concepts of DSS were articulated as Management Decision Systems by Scott Morton in the early 1970's (Sprague & Carlson, 1982).

Historically, DSS's were not well accepted by practitioners in the early developmental stages. This was due to underdeveloped graphic user interfaces (GUI) and the inability for models to readily communicate with (i.e., pass information, inputs, and results to) each other (Scheibe, 2003; Sprague & Carlson, 1982). However, with the advancement of GUI technology and model interfacing, DSS's were extensively accepted. DSS's are now used in almost every field: businesses, hospitals, governments, non-profits and universities (Eom & Lee, 1990; Eom, Lee, Kim, & Somarajan, 1998; Eom & Kim, 2006; Rodriguez, Vitoriano, & Montero, 2010).

8.1.1 DSS Components

A DSS is made up primarily of three independent yet interconnected components, with which the user can interact: the Database Management System (DBMS), the Model Base Management System (MBMS), and the Dialog Generation and Management System (DGMS) (Sprague & Carlson, 1982). See Figure 2-6.

1. Dialog Generation and Management System. Since the DSS is used to solve problems requiring semi-structured decisions (i.e., for which no algorithm can be prescribed), no set solution algorithm can be embedded in the system to answer all user questions. Consequently, the manager/decision maker must supply the algorithm/intelligence to run and analyze appropriate models as the decision making process evolves. This furnishing of the algorithm is done by the user through the DGMS. The key usability factor of the entire DSS thus depends significantly on how well the DGMS GUI is developed to meet the user's needs, especially since all the capabilities of the system are channeled and implemented through the DGMS (Sprague & Carlson, 1982).
2. Model Base Management System. The model base integrates data access to decision models to provide results in the form of outputs directed to the user as well as to the data base. The decision models that make up the model base include strategic, tactical, and operational models (Sprague & Carlson, 1982).
3. Data Base Management System. This component is involved in the collection and storage of data to enable transactional processing (queries, retrievals, etc.) (Sprague & Carlson, 1982).

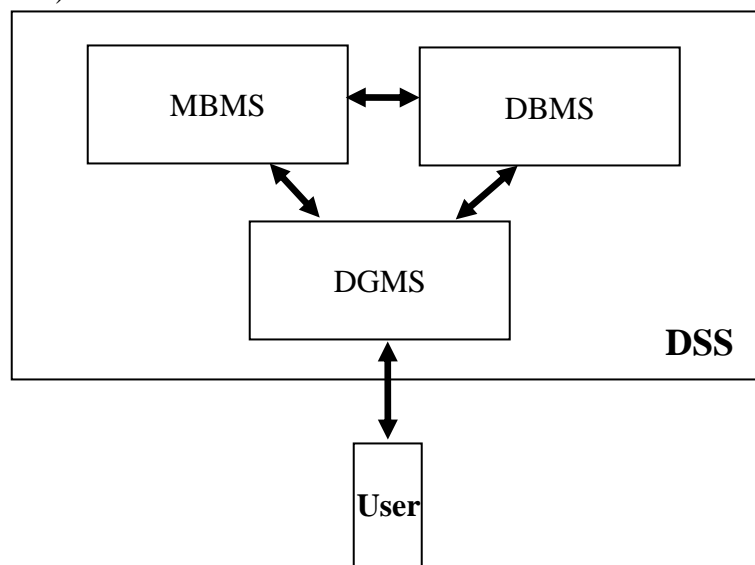


Figure 2-6. DSS Model Components (adapted from (Sprague & Carlson, 1982))

8.1.2 Decision Support and Geographic Information Systems (GIS)

Much business data, and most disaster related data, have locale-specific information (Crossland, Wynne, & Perkins, 1995; Levy, Hartmann, Li, An, & Asgary, 2007). The locale specific information (spatial data) enhances the ability of a decision maker to make better decisions. When spatial data are integrated into the DBMS of a DSS and can integrate seamlessly with the MBMS and DGMS, the DSS is called a *spatial* decision support system (SDSS).

Geographic Information Systems (GIS) organize and analyze spatial data to extract significant information regarding a system (Crossland et al., 1995). However, GIS, as versions of relational database management systems, do not lend themselves as useful tools when making unstructured decisions (West & Hess, 2002). Scheibe (2003) recommends a spatial decision support system, wherein the model base is from the DSS, and the spatial database and the visualization is provided via a GIS, together enhancing the decision making process.

8.1.3 Spatial Decision Support Systems and Disasters.

The spatial nature of disasters has led to special-purpose SDSS. Historically, DSS utilized to analyze disasters emphasized specific disaster types in specific locations (e.g., earthquakes in California). Later, for purposes of usability and flexibility, there was a shift into modular systems that emphasized models and methodologies; an example of this emphasis, which is of particular interest in disaster management research, is the HAZUS SDSS, which was built and is supported by the United States Federal Emergency Management Agency (FEMA) (Rodriguez et al., 2010).

There have been significant applications of DSS to various disaster scenarios such as humanitarian relief logistics (Lei, 2007), nuclear emergencies (Papamichail & French, 2005), epidemics (Arora, Raghu, & Vinze, 2010), terrorist attacks (Mendonça, 2007), and triage decision making (Amram, Schuurman, & Hameed, 2011). For more applications of DSS, including SDSS, see *Decision Support for Emergency Situations* by Van de Walle et al. (Van de Walle & Turoff, 2008).

DSS have significantly contributed in the disaster preparation and planning process as a tool, by providing disaster scenario analysis information and consequently encouraging community decision makers to be mindful and prepared for future disasters (Rodriguez et al., 2010; Van de Walle & Turoff, 2008). For example, HAZUS has been used by communities to evaluate hazard risk for purposes of investment in disaster preparation initiatives.

8.1.4 Disasters and Appropriate Considerations for DSS Components

There is a significant need for DSS that evaluate tradeoffs between mitigative and recovery-based strategies. Such DSS have to consider the repetitive nature of many types of disasters – that is, disasters can and *do* reoccur – as they impact geographic locales (Amram et al., 2011; Van de Walle & Turoff, 2008).

Furthermore, in regards to the data module, a disaster SDSS should be able to capture and analyze temporal data, since disasters and associated decision making are dynamic in nature.

8.2 Mathematical Programming

Mathematical programming (MP) refers to the search algorithm used in determining the best set of decision values, which result in the best possible objective value for the proposed constrained math model. While computers are used to aid in evaluating the MP model, the word programming in this case is related to planning and not computer programming.

The type of mathematical programming selected is dependent on the nature of the objectives, constraints and the decisions. For example, if the decisions are all binary variables, then the type of programming used is binary integer programming; if there are multiple objectives, then one can use either multi-objective or goal programming (setting the objectives as constraints). If the parameters are stochastic instead of deterministic, then stochastic programming may be used; if the objective or constraint functions are non-linear, then non-linear programming is used - (there are exceptions; e.g. if the objective function is separable, one could linearize the function and use linear programming if all other assumptions hold (proportionality, additivity, deterministic, divisibility)).

8.2.1 Mathematical Programming & Applications to DOM

The application of Operations Research / Management Science models in DOM research tends to be phase specific, particularly aimed at emergency response (Altay & Green, 2006, Galindo & Batta, 2013). For example, see Schryen et al. (2015), Sheu (2007), Kovacs & Spens (2007), Salmeron & Apte (2010).

Research on the development phase of DOM, also exists; for example, Lund (2002) using a two-stage linear programming problem (lpp) formulation, minimized the expected value of costs attributed to flood damages, long-term mitigative options, and emergency actions. Dodo, Xu, Davidson, and Nozick (2005), in work on earthquakes, used an lpp formulation that addressed mitigative *and* recovery costs. Similarly, Dodo, Davidson, Xu, and Nozick (2007) used an lpp model with a multi-objective function (minimize risk; minimize mitigation costs) deciding among mitigation decisions. Legg, Davidson, and Nozick (2012) replicated Dodo et al. (2007), except they applied the model to a hurricane scenario. Again recovery considerations were not incorporated.

Other research has considered non-economic measures; Miles & Chang (2006), examined the socioeconomic recovery of a community in the face of earthquakes. Various scenarios were evaluated under ‘*no action*’ and ‘*mitigative action*’ using a simulation model. Vaziri, Davidson, Nozick, and Hosseini (2010) built their model off of Dodo et al. (2007), under an earthquake scenario; the objective function however incorporated *human life*.

More recently though, Edrissi, Poorzahedy, Nassiri, and Noureinejad (2013), citing the need for integration across phases, developed an OR/MS model, explicitly considering mitigation, preparedness, and response phases, yet excluding recovery. However, Edrissi did not model tradeoffs between the phase decisions, including the long-term ones, which is critical in disaster planning.

The current state of the literature tends to underplay three key aspects of the complexity of actual disasters. First, prior work in analytical DOM models are predicated on an isolated hazard event, disregarding the recurrent nature of some hazards, e.g. natural hazards (Chacko, 2012; Salmerón & Apte, 2010). Second, even when dealing with a single disaster event, the literature does not include the importance of modeling both recovery and mitigation in an integrative fashion. Both these issues need to be explicitly considered, as Mileti (1999), Mileti and Gailus (2005), and Van de Walle and Turoff (2008) note. Godschalk and Salvesen (2004) and the City of Portsmouth (2010) point to the importance of limiting repetitive disaster damages (e.g., forbidding or buying out resettlements in flood plains). Such modeling has the potential to alleviate suffering and human loss, to align the community more with its social goals, and to reduce cost. A more realistic approach in the strategic sense is to address disasters within an explicit horizon or long time window (say 20 or 30 years), thereby allowing inclusion of inter-temporal factors across multiple events (Mileti, 1999; Mileti & Gailus, 2005; Psaraftis,

Tharakan, & Ceder, 1986; Van de Walle & Turoff, 2008). Finally, analytical models do not consider the multi-hazard nature of risk, as highlighted in section 7 of this chapter.

8.3 Simulation

If mathematical relationships are simple to model, it is preferred to develop closed form mathematical formulations. However, in most real life cases such as the one this dissertation attempts to model, it is difficult to evaluate the entire model analytically. As a result, simulation is a suitable alternative (Hillier & Lieberman, 2010; Law, 2007).

Simulation has seen much use in various applications due to its powerful flexibility in modeling complex stochastic systems (Hillier & Lieberman, 2010). Consequently, simulation can be used as a modeling technique to imitate a complex system for purposes of experimentation, analysis, or determination of system characteristics.

The critical benefit of simulation is that in an actual system, we may not be able to experiment. However, with simulation, one can change the system input and run a number of scenarios to determine system characteristics. As one increases the number of replications, we expect to see the long-term behavior of the system.

8.3.1 Characterization of Types of Simulation Models.

In dynamic simulation, time plays a role. Some simulations are fixed-time-increment simulations (in which case, the fixed time increment should be less than the shortest event time); others are next-event simulations. The simulation used in this dissertation is next-event simulation, whereby the clock is forced to shift to the next event; this is also known as discrete event simulation, because the transitions between event states are discrete.

8.3.2 Simulation and disasters

There are various excellent computer models that are available for assessing the impact of infrastructural mitigative action. An example of such a model is HAZUS. HAZUS is essentially a loss estimation model, developed by FEMA. The inputs to the model are disaster descriptors and built environment attributes.

There are specifically three reasons why this dissertation does not use HAZUS: (i). HAZUS limits the decision variables to choices that affect the built environment. (ii). HAZUS is essentially a loss estimation model, HAZUS does not allow for recovery. (iii). Building our own mathematical and simulation model allows us to experiment with the impact of different model parameters, such as disaster arrival times, disaster recovery times, and to conduct (sensitivity analysis) on the robustness of decision policies. HAZUS does not afford us these opportunities.

Our analysis requires an integrated model that evaluates the impact of policies, both mitigative and recovery-based in nature. Our policies contain a portfolio of both mitigative and recovery strategies.

8.5 Uncertainty, Fuzzy Sets, and Fuzzy Decision Making

Uncertainty is generally handled using probabilistic methods. However, there are uncertainty situations where the data available are in nominal/categorical form. In these cases, uncertainty is not due to randomness, but rather is due to imprecision or fuzziness caused by the nature of linguistics (Bellman & Zadeh, 1970). In such cases, fuzzy techniques are preferable. This is fundamentally because of the foundations of measurement theory – to perform aggregation techniques such as addition and multiplication, data on ratio/absolute scales are required (Turksen, 1992).

8.5.1 Fuzzy Sets and Decision Making

Fuzzy sets have been used in varied scenarios, as an accepted mathematical technique, to deal with uncertainty (Rees, Deane, Rakes, & Baker, 2011). Fuzzy sets are membership sets that reflect an entity's level of membership in a set. In fuzzy sets, one (1) represents full membership while zero (0) represents non-membership. Fuzzy sets provide information on membership level and are not to be seen as probability distributions. However, these sets can be extended (added and multiplied). Extension of fuzzy set intervals were first shown by Zadeh using alpha cuts (Zadeh, 1969). Dong and Wong have subsequently illustrated how such extensions may be performed and applied (Dong & Wong, 1987).

Fuzzy techniques are appropriate in situations where one needs to account for the subjectivity in human evaluations. For example, to model subjective evaluations of a threat on particular assets, subjective ratings may be obtained from security experts, thereby providing the values for graded membership in a fuzzy set (Rees et al., 2011). The literature also notes that fuzzy information from many experts may be better than a crisp estimation from one expert (Rees et al., 2011).

Fuzzy programming techniques were made popular in the 1970s with their application to multi criteria linear optimization techniques by viewing constraints as elastic (Dubois, 2011). Ever since then, fuzzy decision making techniques have had many applications including supply chain analysis, see (Ho, Xu, & Dey, 2010); transportation (Smith, 2012); and to a wide spectrum of other applications, including linguistic decision analysis – see Dubois (2011); Kahraman (2007); Wang (2000). Moreover, many classical OR/MS models (Turksen, 1992) have been “fuzzified” including techniques such as fuzzy integer programming (He, Ho, Man, & Xu, 2012), fuzzy non-linear programming (Tay, Jee, & Lim, 2012), fuzzy AHP (Lo & Wen, 2010), fuzzy

Data Envelopment Analysis (DEA) - and its many variations (Hatami-Marbini, Emrouznejad, & Tavana, 2011), and fuzzy decision analysis (Watson, Weiss, & Donnell, 1979).

8.5.2 Fuzzy Sets and Disasters

Fuzzy sets have been used in various applications to characterize uncertainty. For example, fuzzy sets have been successfully applied to cyber-security planning (Rees et al., 2011), and to disasters (Iliadis & Spartalis, 2009), where fuzzy sets were used to capture parameter uncertainty.

**CHAPTER 3: SUSTAINABLE DISASTER OPERATIONS MANAGEMENT:
A PLANNING FRAMEWORK**

SUSTAINABLE DISASTER OPERATIONS MANAGEMENT: A PLANNING FRAMEWORK

ABSTRACT

Advancing disaster operations planning has significant implications given the devastating impress of disasters. We argue the need for a fundamental shift in the motivation of archetypal disaster planning models, highlighting the insufficiency of planning motivated solely around the disaster. We contend that for the principal issue of community viability, disaster-planning models must extend their focus from the disaster to include larger quality of life systems, advocating for a sustainability-based planning framework. Drawing upon a review of the disaster operations, planning and sustainability literature, we identify eight primary dimensions of sustainable disaster operations management, weaving them into a planning framework.

Keywords: Disaster Planning, Disaster Operations Management, Sustainable Disaster Management

SUSTAINABLE DISASTER OPERATIONS MANAGEMENT: A PLANNING FRAMEWORK

1.0 INTRODUCTION

During the past century, demographic trends in urban locales have invariably led to the concentration of capital investment around these human ‘hotspots,’ unfortunately also resulting in an increase in disaster vulnerability of humans, both socially and economically (Cutter, et al., 2008; Tierney, 2009; Tufekci & Wallace, 1998). A recent and poignant example in the United States is the effect of Hurricane Sandy on New York City in 2012. Unfortunately, disasters are a worldwide problem, and as shown in Figure 1, they are an increasingly costly one. With increasing impact of disasters on quality of life and economic support structures, improving the state-of-the-art in disaster operations management has significant implications.

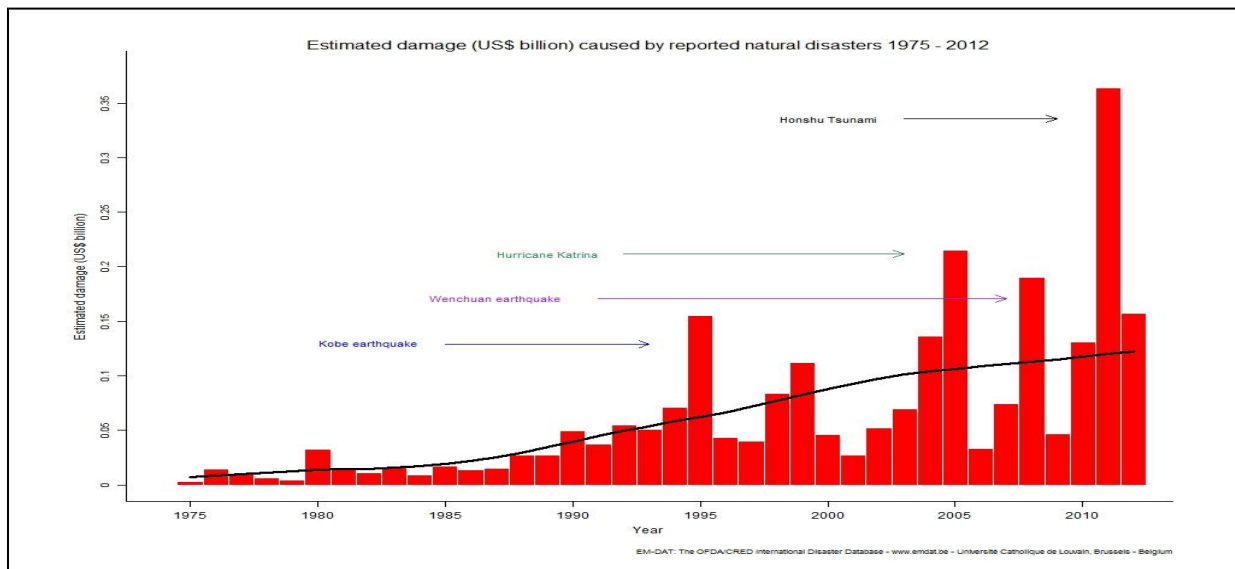


Figure 3-1: Natural Hazard Damage Trends (EM-DAT, 2013)

Disaster operations management (DOM), the operations motivation of disaster management, is a significantly complicated process. Central to the complexity is an inherently socio-technical process whereby stakeholders perform technical activities under inter-temporal

and spatial externalities. These technical activities include actions taken to recover and establish the affected community to a state of normalcy, and actions taken to minimize future disaster impact (Altay & Green, 2006, Lettieri, Masella, & Radaelli, 2009). These actions are carried out in all phases of the disaster management cycle: mitigation, preparedness, response, and recovery (Altay & Green, 2006; Tomasini & Van Wassenhove, 2009). Activities carried out in the first two phases are focused on minimizing the social, economic and physical impact prior to a disaster. Immediately after a disaster, in the response phase, emergency responders initiate activities that are focused on managing after-disaster effects. Finally, activities in the recovery phase split into two sub-phases, short-term and long-term recovery (Holguín-Veras, Pérez, Jaller, Van Wassenhove, & Aros-Vera, 2013; Tierney, Lindell, & Perry, 2001), where short-term recovery refers to the transitional stage between response and long-term recovery, and long-term recovery is focused on returning the affected community to a functioning state (this state can be better or worse than its prior state).

As is evident from the earlier discussion, there exists an emergency and a sustainability element to DOM: Some DOM activities are motivated around the emergency of the event itself: immediately before, during, and immediately after the disaster event, while other activities are focused on the longer-term sustainability of the system. However, typical disaster planning models have their focus around the disaster event; this motivation is insufficient (Alexander, 2005; Mileti, 1999; Turner et al., 2003). There is a need to widen the focus both temporally and to broader quality of life systems external to the perturbation for the principal issues of long-term community stability, viability and equitability. Stated differently, there is need for a DOM planning model that is not motivated around the disaster event in isolation but motivated by the larger context of the perturbation – there is need for a sustainable DOM planning model. While

various disaster-planning models have been proposed, such as Faulkner (2001), Holguin-Veras et al. (2013), Salmeron and Apte (2010), Tobin (1999), and Turner et al. (2003), there is no well-defined framework in which sustainability is the emphasis of a DOM planning model.

In the early 1990s, disaster researchers initiated efforts applying the principles of sustainable development to disasters predicated on the notion that disasters threaten the long-term viability of a community (Dovers, 2004). Due to the inherent long-term emphasis of the sustainability paradigm, disaster mitigation was traditionally viewed as the basis to sustainable DOM (Pearce, 2003), essential to breaking the disaster cycle of damage, reconstruction, and repeated damage (Godschalk, 2003). Unlike preparedness, response, and short-term recovery, which are immediate and reactive to the disaster event, disaster mitigation is proactive (Godschalk, 2003). However, sustainable disaster management, due to its long-term focus, does not inherently consider the immediate emergency (response and preparedness) type activities (Aguierre, 2002; McEntire, 2005) that are crucial to alleviating immediate human suffering. Accordingly, there is also a need to develop a sustainable DOM planning framework that integrates the emergency elements.

Consequently, the purpose of this paper is to develop a DOM planning framework that captures the mechanisms and objectives central to sustainability and, in addition, to integrate the planning across the emergency and sustainability elements that exist in a DOM cycle.

The remaining sections of this paper are organized as follows: section two is a survey of the literature providing background related to disaster management and, in particular, sustainable disaster management. Section three formulates eight features or dimensions of sustainable DOM planning based on the literature review. Section four starts with a definition of planning, and from that derives three relationships or linkages inherent therein. Section five derives the new

framework based on the primary dimensions surfaced in section three and the three linkages elicited in section four. In section six we list some potential benefits of the new planning model, and finally, in section seven, we provide conclusions and possible future research directions.

2.0 LITERATURE SURVEY

This survey begins with definitions of the foundational terms discussed in the paper. The discussion that follows provides an overview of key paradigms applied to disaster management, and, in particular, the sustainable development (SD) paradigm.

2.1 Foundational Definitions

Disasters

The intrinsic nature of a disaster is central to any discussion on disaster management. To the layperson, disasters, emergencies, and hazards may be identical, but the discussions on these terms are far more intricate. The various philosophical paradigms by which disasters have been defined have included: functionalism, social constructionism, postmodernism, conflict-based theories, and political economy theories (Mileti, 1999; Pearce, 2000; Tierney et al., 2001). While the definition of the term ‘disaster’ is contentious and researchers are not unified on a single definition (Holguin-Veras et al., 2012; Quarantelli, 1998a), discussions in this area are abundant. Interested readers are encouraged to examine publications such as Perry (2005, 2006) and Quarantelli (1985, 1998a), which provide a comprehensive review of this issue.

The disaster definition used in this paper, consistent with recent adaptations in the operations management literature as in Holguin-Veras et al. (2012), is adapted from Pearce (2000: 22): “... a non-routine event that exceeds the capacity of the affected *community* to respond to it in such a way as to save lives, to preserve property, and to maintain the social, ecological, economic, and political stability of the affected *community*.” We have replaced the

original term “area/region” with “community” (italicized) to frame the disaster definition to those disasters that affect human populations – “while most disasters impact humans, not all do” (Quarantelli, 1998b, p.1). Accordingly, this paper loosely defines community as a group of people characterized by a common geographical boundary, small enough to be appropriate for participatory decision-making. This is consistent with Mileti (1999) and the broad definition by the Merriam-Webster dictionary (Community, n.d.).

Disaster Management

Disaster management (DM) definitions commonly use language that would indicate it as a series of activities with the goal of alleviating disaster effects, as can be noted in definitions offered by Altay and Green (2006), Lettieri et al. (2009), and Quarantelli (1988). However, the definition we use, consistent with Drucker’s emphasis that management is a process of establishing common objectives (Greenwood, 1981), is adapted from Pearce (2000:28). Pearce (2000) defines DM as the process of establishing common objectives among actors for the purpose of planning for and dealing with disaster effects, such as limiting the future impact of disasters and recovery back to a state of normalcy. This paper adopts Pearce’s definition as it emphasizes both the outcomes and the establishment of common goals as principal to the DM process.

DOM frames the scope of DM to the operational issues of disasters. It is important to note however that the term disaster management has at times been broadly used to refer to DOM. For a comprehensive historical overview on DOM see Pearce (2003).

2.2 Disaster Management Paradigms

Over the past three decades, various paradigms have been proposed to advance disaster management research and its praxis, including: comprehensive emergency management, disaster

resistance, vulnerability, resilience, and sustainability (McEntire, 2005; McEntire, Fuller, Johnston & Weber, 2002). For an extensive comparison see McEntire et al. (2002).

More recently however, sustainability has been emphasized as a disaster management paradigm (Asprone, Prota, & Manfredi, 2014; McEntire, 2005) for various reasons, primarily the need to consider broader implications and interrelationships (Turner et al., 2003). Appropriately then, this paper considers sustainability as it broadens and refocuses DOM to include the interdependence of environment, human, and economic development domains; and, the operationalization by various mechanisms of diverse functional and spatio-temporal scales.

Sustainable Development

In lieu of staggering disaster-related losses, the short-term focus of disaster policies, and the lack of emphasis on systems and linkages beyond the immediate disaster and affected entity, Godschalk et al. (1998), Mileti (1999), and Turner et al. (2003) advocated the need for a different paradigm to disaster management, i.e., the sustainability paradigm. The concept of sustainable development, as first concisely articulated by the World Commission on Environment and Development (WCED), was a vision of ecological concern, inter-generational equity, and economic development (National Research Council [NRC], 2006). The WCED's definition of sustainable development, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987: 43), has since been adapted for DM. In addition, Mileti's seminal work in this area defined sustainable disaster management, in particular mitigation, as the capacity of a community to manage the effects of a disaster without significant external help (Mileti, 1999). These two definitions have been the premise of all other conceptualizations in this area (McEntire, 2005).

The sustainability paradigm has contributed significantly to disaster research, as noted by McEntire et al. (2002) and McEntire (2005), particularly because it emphasizes a community-driven DM process; it adds to the understanding of the link between actions (particularly those of development – mitigation and long term recovery) and disasters; and it emphasizes long-term viability. However, it is not without its criticisms, most of which have been addressed by the [U.S.] National Research Council (NRC, 2006) and Pearce (2003). A critique that has not been addressed yet and is significant to the purpose of this paper is the temporal and systemic exclusivity inherent in the sustainability paradigm (Aguierre, 2002; Berke, 1995; McEntire, 2005; McEntire et al., 2002). In particular, McEntire and Aguirre argue that the sustainability paradigm excludes short-term DOM activities – preparedness, response and short-term recovery, for the sake of long-term development type activities such as mitigation and long-term recovery. Consequently, both McEntire and Aguirre posit that sustainability as a paradigm fails to capture the entire process of DOM.

Nonetheless, we contend that, although the generic goal of sustainability is long-term viability, tradeoffs between short-term goals and long term goals have to be made. This is part of the tension that this paper addresses, as noted earlier. Moreover, to create an integrative planning framework for sustainable DOM, this paper needs to first highlight dimensions central to the sustainable DOM process. The next section provides a discussion of these issues.

3.0 SUSTAINABLE DISASTER OPERATIONS MANAGEMENT

This section first provides, from the literature, eight different dimensions (or aspects or features) of sustainable DOM. These eight are then partitioned into two groups, the first related to DOM *objectives* and *goals*, and the second to *mechanisms* that operationalize sustainability.

3.1 Dimensions Central to Sustainability

The principle dimensions of sustainable DOM, broadly characterized and anticipated by or explicitly included by Asprone et al. (2014), Beatley (1998), Berke (1995), Godschalk et al. (1998), Mileti (1999), NRC (2006), Smith and Wenger (2007), and Tierney et al. (2001), are summarized in Table 1. Table 2 provides a description of the dimension terms used in Table 1.

Papers that predicate sustainable dimensions based on research not in primary sources are not listed. For example, Adie (2001) and Pearce (2000, 2003) establish their entire list of dimensions from Mileti (1999), and subsequently are not included in Table 1. Because our focus in this paper is on those dimensions central to sustainability in the disaster operations context, dimensions seen in urban planning (Beatley, 1995; Wheeler, 2013) and the business literature (Kleindorfer, Singhal, & Wassenhove, 2005; Linton, Klassen, & Jayaraman, 2007; Porter & Kramer, 2006, 2011; Prahalad & Hamel, 1994), despite significant consistency, are not included here. The list of eight dimensions is as follows: environmental/ecology; social/quality of life/equity; economic development; engagement; resilience; integrative DOM; resource conservation; and long-term planning.

3.2 A Partitioning of DOM Dimensions

Whereas Mileti (1999) frames the sustainability dimensions loosely as objectives, we contend that due to the nature of those dimensions, it is more appropriate to broadly categorize them as objectives and mechanisms (processes by which sustainability is operationalized). For example, a community does not pursue engagement (public participation) as an end goal, but rather as a means to determining the populace's values, which is essential in deciding among and balancing interdependent and competing objectives. Hence, we partition the dimensions into two groups: the triad of objectives (listed first above), and the remaining five mechanisms. This partitioning is consistent with general indications in Tierney et al. (2001) and NRC (2006).

Table 3-1

Literature Review: Summary of Sustainability Dimensions in DOM

Reference	Dimensions of Sustainable DOM								
	Objectives			Mechanisms					
	Environmental / Ecology	Social/ Quality of Life / Equity	Economic Development	Engagement	Resilience	Integrative DOM	Resource Conservation	Long Term Planning	Others
Berke (1995)	✓	✓		✓			✓		✓
Godschalk et al.(1998)	✓	✓	✓	✓	✓		✓		
Beatley (1998)	✓	✓	✓		✓	✓	✓		✓
Mileti (1999)	✓	✓	✓	✓	✓		✓		
Tierney et al. (2001)	✓	✓	✓	✓		✓			✓
NRC (2006)	✓	✓	✓	✓					
Smith and Wenger (2007)	✓	✓	✓	✓	✓				
Asprone et al.(2014)	✓	✓	✓	✓	✓			✓	

Table 3- 2

Description of terms used in Table 1

Terms	Description of Terms
Environmental / Ecology	Maintain the ecological carrying capacity of an environment and if possible enhance environmental quality (Mileti, 1999)
Social/ Quality of Life / Equity	Maintain and improve quality of life standards for all community members, particularly the disadvantaged. Moreover ensure equity (equal chances for all to an opportunity to a satisfying life) for current and future generations (Mileti, 1999; NRC, 2006)
Economic Development	Foster a strong local economy, which includes both natural and man-made capital, to ensure better and sustainable living standards (Godschalk et al., 1998; Mileti, 1999; NRC, 2006)
Resilience	Adapt to the extreme event and return to a state of normalcy (Manyena, 2006)
Engagement	Provide full participation of all affected stakeholders, which includes the community itself. (Mileti, 1999; NRC, 2006)
Long term Planning	Plan for disasters beyond an isolated event, rather considering a decision horizon sufficiently long to capture the externalities arising from epiphenomena
Integrative DOM	Plan DOM in an integrative manner across all four DM phases and across competing objectives
Resource Conservation	Use resources efficiently given ecological and economical limitations.

3.2.1 Objectives

Environmental concern, enhancement of quality of life (inclusive of equity and broad social issues), and economic development can be broadly categorized as objectives for sustainable DOM (NRC, 2006). These distinct objectives, traditionally viewed as competing goals, are in fact also interdependent, and achieving a balance across these broader objectives can be operationalized using engagement (NRC, 2006).

3.2.2 Mechanisms

Besides engagement, the other mechanisms repeatedly mentioned in the literature include resilience, resource conservation, integration, and long-term planning. While some authors may not have intentionally framed long-term planning and integration explicitly as sustainable mechanisms, it becomes apparent while reviewing the literature that these additions are consistent and in fact central to the spirit of sustainability.

Engagement (Public Participation)

The risk of stakeholder exclusion in the disaster planning process is the underdevelopment of local community capacities for subsequent disaster(s), as evidenced historically by largely unsuccessful and inefficient DM processes (Berke, Kartez, & Wenger, 1993; Pearce, 2003). Conversely, public participation on decisions that directly affect the public is apt to have significant stakeholder commitment (Thomas, 1993, 2012). Moreover, engagement is critical to disaster planning, as it eventually results in wider access to resources (NRC, 2006). For a comprehensive guide to operationalizing participatory planning in DOM see Pearce (2003) and Adie (2001, ch. 3); for a general guide, see Thomas (1995) and Thomas (2012, ch. 9).

The type of DOM planning issues that require community acceptance is central to the discussion in this paper. In this regard, a principal discriminant in classifying planning issues is

the impact of engagement on decision quality (Thomas, 2012). In regard to this concern, Thomas (1993, 1995, 2012), borrowing from the management literature (Vroom & Yetton, 1973; Vroom & Jago, 1988), highlights the balance between two key issues: decision quality (contingent on “objective aspects of the decision”) and decision acceptability (contingent on “subjective aspects of the decision”) (Field, 1979:1). If the nature of the eventual planning decision is highly technical in nature, public participation may not be effective; however, decisions that require public acceptance for successful implementation should consider engagement (Thomas, 1995, 2012). Consequently, in regards to sustainable DOM, the discussion on objectives requires engagement (NRC, 2006); this notion is consistent with Berke et al. (1993) and Pearce (2003). Moreover, engagement provides an avenue in which the affected community ascribes varying levels of value (NRC, 2006).

Integrative DOM

In the context of sustainable DOM, the following elements can be considered as part of a broader theme on integration:

1. Integrating the triadic objectives: An important perspective to long-term viability is shifting the emphasis from competing objectives to interdependent ones. For example, economic development and ecological conservation are traditionally managed as opposing and competing objectives. Though these objective dimensions are in competition, by focusing on the interdependencies between the objectives and emphasizing those, shared value is created (Porter & Kramer, 2011). Broadly speaking, Porter and Kramer (2006, 2011) suggests that one can do this by placing focus on those elements that result in growth along all the ‘competing’ dimensions.

2. Integrating emergency and sustainability elements in DOM: While the emphasis of sustainability is inherently a long-term perspective, as seen in its emphasis in mitigation and long-term recovery, it should allow for the consideration and integration of decisions across the short-term disaster event (emergency) oriented phases. Moreover, as discussed in disaster research by Greiving et al. (2012) and Drabczyk (2007), and as demonstrated in the quantitative OR/MS research by Edrissi, Poorzahedy, Nassiri and Nourinejad (2013) and Tufeccki and Wallace (1998); integrated disaster decisions result in better resource allocation decisions and consequently result in less wastage and better resource conservation.

Resource conservation

Berke (1995) and Mileti (1999) emphasize the need to efficiently use resources (broadly defined) in the context of intergenerational equity – ensuring that decisions made today by the current generation do not limit future investment decisions by the next generation. Specifically, Beatley (1998) emphasizes the importance of recognizing ecological limits on resources available and Godschalk et al. (1998) highlights the need to be cost-effective.

In summary, decisions and actions taken should lay importance on capitalizing available resources to ensure the greatest return and least wastage while considering limitations of resources, within a long-term perspective.

Long-term planning

Long-term planning is an intrinsic component of sustainable DOM, particularly given the definition of sustainability – meeting present needs without affecting the ability of future generations to meet their needs. Moreover, the recurrent nature of disasters (particularly natural hazards) must be explicitly considered in the planning process, in that they are not isolated

events (Mileti, 1999; Mileti & Gailus, 2005; Salmeron & Apte, 2010). Long-term planning can be incorporated into the DOM planning process by shifting the emphasis in planning for a single event epoch to a longer decision horizon (Asprone et al., 2014; Mileti, 1999; Turner et al., 2003). For example, Godschalk and Salvesen (2004) emphasize the importance of considering the recurrent nature of natural hazards. In particular, they point to the importance of limiting repetitive disaster damages (e.g., cases of settlements in flood plains) as one way of sustainable DOM. This notion is also supported by various applied publications such as the City of Portsmouth flood management plan (City of Portsmouth, 2010) and flooding research in the tidewater region of Virginia (Mitchell, Hershner, Hermann, Schatt, & Eggington, 2013).

Resilience

While there has traditionally been a strong linkage between the concepts of sustainability and resilience, disagreements regarding their exact relationship exist. Resilience as a dimension of sustainability is the form of relationship that this paper adopts as supported in the following publications (Asprone et al., 2014; Mileti, 1999; Pearce, 2003; Smith & Wenger, 2007); specifically, the view here holds that sustainability is a broader paradigm while resilience is specific to the extreme event (Asprone et al., 2014; Turner et al., 2003).

Resilience is central to a community's ability to adapt to an extreme event and in the long-run to the community's viability. The resilience definition we adopt is as follows: resilience is the capacity of a system/community to adapt to an extreme event and 'bounce forward' (as Manyena would put it) to a different state (Manyena, 2006; Norris, Stevens, B.Pfefferbaum, Wyche, & R.Pfefferbaum, 2008). The adoption and rapid expansion of the resilience concept outside the physical sciences is due to Holling's (1973) seminal work in ecology. Yet resilience is also a fiercely contested concept with rich historical disciplinary

traditions (Alexander, 2013; Norris et al., 2008). There are more granular distinctions in the disaster literature and interested readers can see Norris et al. (2008), Zhou et al. (2010), and Alexander (2013) for a comprehensive discussion.

To support the operationalization of the resilience concept, Gilbert (2010), Mitchell (2012), and Weischelgartner (2014) recommend including outcome-oriented components in conceptualizations. These outcomes can be evaluated and can provide a measure of the process effectiveness (Gilbert, 2010). Various researchers such as Bruneau et al. (2003), Zobel (2011) and Zobel and Khansa (2014) have characterized the resilience measure based on an entity's ability to withstand a disaster event and its speed of recovery. In the DOM planning framework, both issues of robustness and speed of recovery are important.

3.3 Existing Sustainable Model Conceptualizations

Two earlier sustainability disaster frameworks proposed by Tobin (1999) and Turner et al. (2003), provide an excellent background from which this paper extends.

Tobin (1999) provides a disaster-planning framework explicitly considering sustainability and resilience. The framework consists of three main elements: mitigation (Waugh, 1996; as cited in Tobin, 1999), recovery (Peacock & Ragsdale, 1997; as cited in Tobin, 1999), and a structural-cognitive model (Tobin & Montz, 1997; as cited in Tobin, 1999). Tobin highlights the interaction between the three models and their resulting community outcomes. However, the sustainability model is constrained to the disaster event and, moreover, does not consider the broader elements of environmental concern, quality of life and economic development.

Turner et al. (2003) provide a broader sustainability framework for the purpose of vulnerability analysis; however the framework does not support disaster planning. While the

framework extends the focus beyond the extreme event, it does not explicitly consider economic development or resilience.

4.0 SUSTAINABLE DOM PLANNING

Utilizing Anthony (1965), Dynes, Quarantelli and Kreps (1972), and Godschalk et al. (1998), DOM planning can be described as a process by which stakeholders specify objectives and select appropriate actions from alternatives, given limited resources (human, supplies, equipment). Note that the definition provides two natural pairings; *stakeholders* and *objectives*, and *actions* and *resources*. The first pairing, which we term linkage 1 (L1), highlights that planning relies on stakeholders to specify and address the interdependencies among objectives. In a similar fashion, the second pairing, linkage 2 (L2), expresses the fact that once linkage L1 is specified, then actions must be chosen to meet the objectives of L1; these actions will consume resources. Additionally we have included linkage 3 (L3) to signify the importance of linking the emergency event planning models with long-term sustainability planning.

4.1 Mapping Sustainable Dimensions onto Planning Linkages

The purpose of this research is to develop a sustainable DOM planning framework. To do this we weave the eight sustainability dimensions into the planning linkages (L1, L2, L3) highlighted above, as shown in Figure 2. Displayed at the top left of Figure 2 are the eight sustainability dimensions we derived from the literature; these dimensions are partitioned into two sections – the triad of sustainability objectives, and the five sustainability mechanisms. At the top right of that figure, we show the planning linkages (L1, L2, and L3).

The first connection we make relates the triad of objectives and L1. In building the framework architecture, first, objectives specified by stakeholders must reflect the triadic sustainable values of economic, ecological, and social development (S1, S2 and S3). Second, the

community must be given the opportunity to set those objectives in a manner consistent with its own values (M1). Resilience (M2) provides a natural linkage between emergency planning and sustainable planning (L3) – resilience to the disaster event sets the stage for longer-term normalcy. Moreover, it can be included as a short-term objective measure, during a single-epoch, which demands a rapid and robust return to normalcy during and after the epoch, as stakeholders determine how to operationalize objective interdependencies. Resource conservation (M3), naturally maps to linkage L2, where suitable actions selected from alternatives will lead to better resource conservancy. Long-term planning (M4) is embodied in linkage L3. Integrative DOM (M5) is essential in linkage L3; that is because it addresses the tension between single-epoch emergency planning for the short-term versus the multi-event long-term sustainable planning. Both these planning elements must be integrated in a manner supportive of each effort. Thus we see that the eight dimensions of sustainability can be added into the three planning linkages in an enriching manner that yields sustainable planning.

4.2 Planning Framework Architecture

The planning framework architecture offered in the lower half of Figure 2 presents all the planning elements with their highlighted linkages. The stakeholder's block is where decisions are generated; these decisions in turn require resource allocation. Based on the decisions made, resource allocations determine the DOM activities implemented for sustainable DOM. Note that with the mapping presented in Figure 2, the planning framework presented allows for linkage between sustainable DOM planning and emergency planning, reflecting the need to address the tension expressed in linkage 3.

Not shown explicitly in Figure 2 are community values, information paths, and feedback loops. These will be added into the final framework derived, see Figure 3.

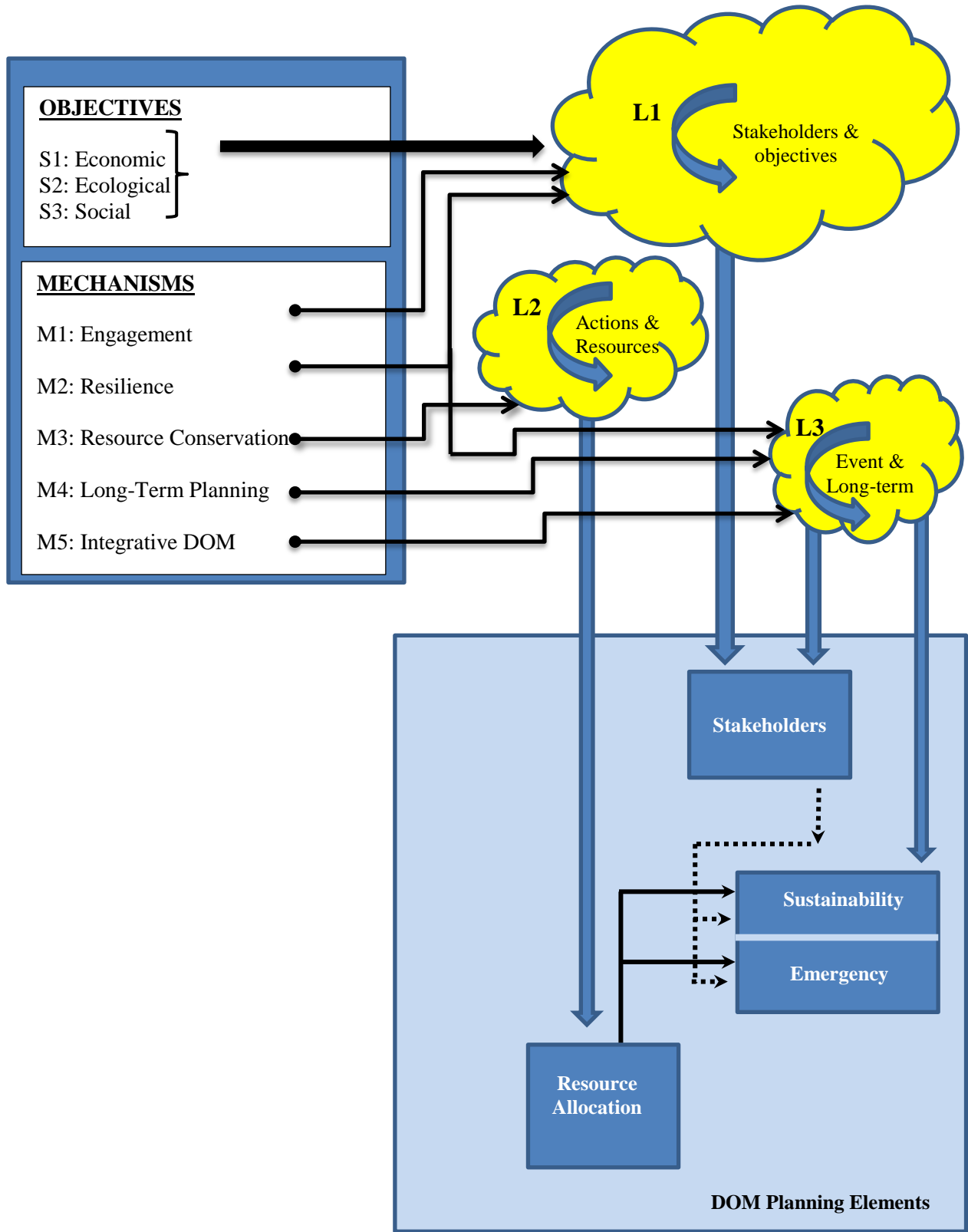


Figure 3-2. Architecture of Sustainable DOM Planning Framework

5.0 A SUSTAINABLE DOM PLANNING FRAMEWORK

Having shown how the sustainability dimensions are linked to the planning framework, we focus on the planning framework itself.

5.1 Framework Description

Note first the community buy-in and policies input of the proposed framework (see Figure 3, blue outline box). The input refers to stakeholder engagement, in particular the levels of value ascribed between the triadic objectives. Stakeholders include: the local community, emergency personnel, FEMA, non-government organizations (NGO's), and local, state, and federal staff. As highlighted earlier in the discussion on engagement, due to the need for 'decision acceptance,' it is vital for stakeholders to be involved in the DOM planning process.

Decision makers may be loosely partitioned into two functional groups: central management and local management. The reason for two separate groups, as noted earlier, is to account for the dichotomous nature of disaster planning: (i) emergency planning, motivated around the disaster event, which deals with the short-term nature of preparing and responding directly to a disaster, and (ii) sustainability planning, motivated around the long-term issues of stability, viability and equability, dealing with development related activities such as mitigation and long-term recovery processes. Stakeholders involved in sustainability and long-term planning are incorporated in central management, and stakeholders involved with emergency planning (e.g. emergency management personnel) in local management. In addition, central management provides regulation for local management functions, as long-term decisions provide bounds on short-term ones. The functional management groups do not have exclusive stakeholder sets, and in some scenarios, may consist of the same individuals.

The framework models each of the DOM activity blocks (mitigation, preparedness, response, and recovery), reflective of the DOM phases, using stakeholder specified objectives (Community Values (CV)). The set of initial CV, representing the state of outcomes, is altered into a new state (better or worse) depending on ambient conditions (disaster characteristics, current community state, etc.) and the decisions prescribed. Decisions by ‘central and local’ are contingent on available resources, CV, and ambient conditions (e.g., the type and level of disaster to strike; the ability of neighboring communities, NGOs, etc., who can help). Furthermore, these decisions provide regulation for the activity blocks by allocating resources to each block.

The notion of information dependency is inconsistent with integration among the four phases. As a further mechanism against information dependency, information regarding the community values, decisions enacted, ambient conditions, and disaster management function states are fed back to the central and local management arms. The key concept is that available information should be used at all times to determine the best management of the entire process. As shown in Figure 3, all information is shared, and decisions and subsequent feedback can occur conterminously. However, due to the nature of disasters, the implementation of the disaster management actions is time-dependent.

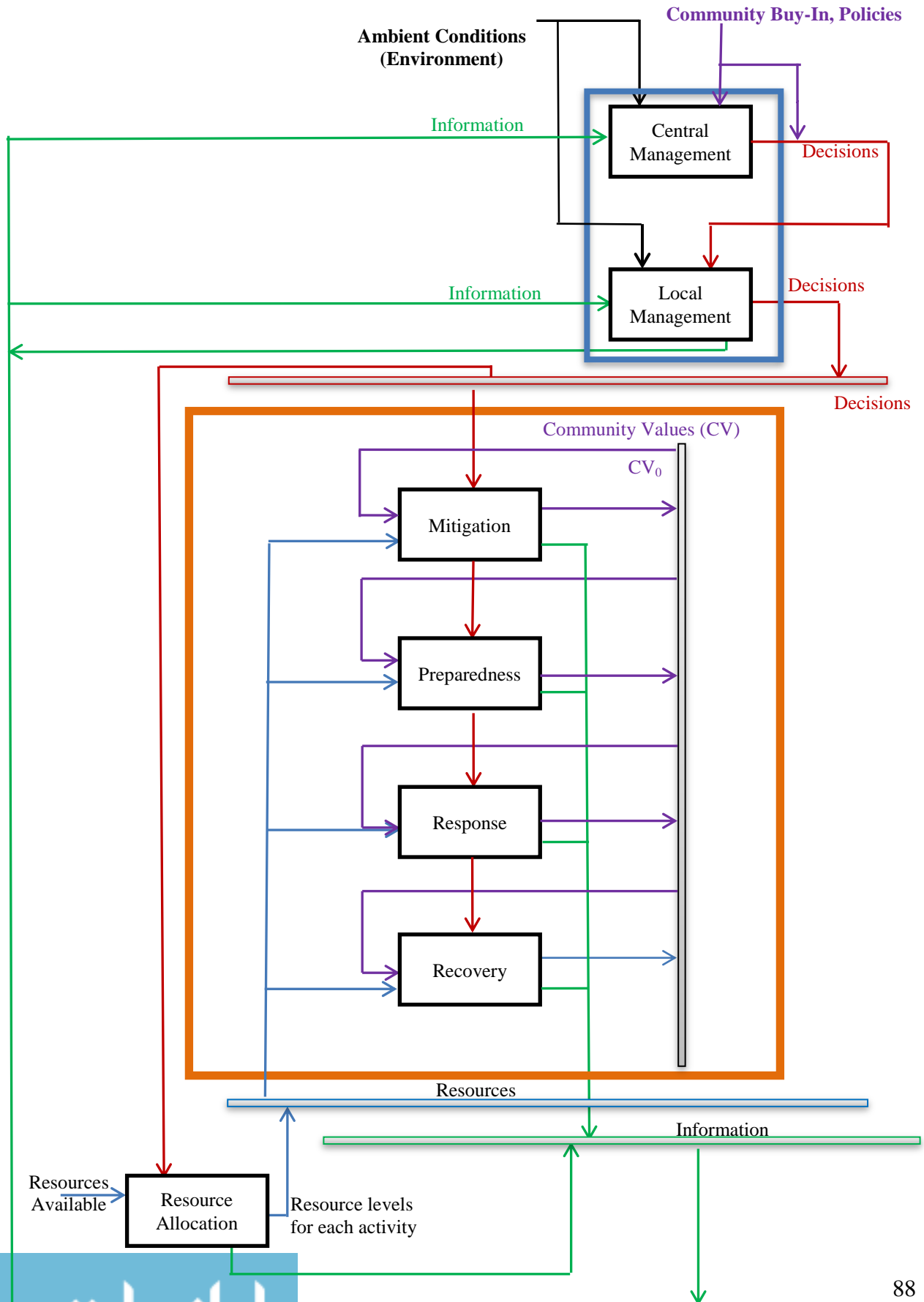


Figure 3-3: Sustainable DOM Planning Framework

5.2 Framework Operationalization

Further examination of the linkages L1, L2, and L3 supplies additional operational criteria to be incorporated in the planning process. These criteria are now discussed.

(i) *Linking stakeholders to sustainability objectives using engagement*

Operationalizing the linkage between engagement and sustainability objectives requires that two key issues be addressed in the framework: (a) the mechanics of actually using community input to balance between sustainable objectives; and (b) the types of performance measures that the community might consider specifying.

Many communities (i.e., the “common citizen”) may not have the technical capacity to define the nominal details through which they would like their values encapsulated. One common technique highlighted in the literature (Burby, Deyle, Godschalk, & Olshansky, 2000) has been to specify values in terms of general goals (e.g., “minimize natural hazard risk”), or as policies that constrain the decision outcome (e.g., “the sum of recovery resources allocated to the wealthy areas of a community should not exceed 50% of available resources”). Subsequently, these general statements can be broken down into specifics based on inputs from experts or case studies, etc.

Stakeholders can also specify objectives used to assess the DOM process. These measures can be represented by either monetary or non-monetary components. For example, a community interested in economic development may opt to track infrastructure value while a second community may consider quality of life issues and track the value of housing for the working-class and/or the elderly as a separate or additional concern. The point to note is that each community/stakeholder must define what it values, as either a single item or aggregation of values suitably weighted or ranked.

By incorporating resilience as a function of its measurable outcomes (rapidity and robustness), and including it as a measure, the changes in CV may then be assessed in the context of system resilience, with attention to both the amount of change and the length of time during which that change persists.

(ii) *Linking the sustainable and emergency planning models*

Operationalizing the linkage between the sustainable and emergency planning models requires that two further issues be addressed: whether (and if so, how) the four decision phases are to be modeled in concert; and, what is an appropriate decision horizon for long-term planning. With respect to the first issue, using the principle that planning models with consistent temporal and objective factors be modeled together, we specify that mitigation and long-term recovery be modeled together, and that response, preparedness, and short-term recovery also be modeled together. With respect to the length of the planning horizon, we stipulate a horizon generally long enough to include multiple recurring disasters and various related epiphenomena over which decisions will be explored. Solutions based on long horizons will hopefully enable the community to see possible ramifications from decisions that are not sustainable.

(iii) *Resource allocation and tradeoff decisions*

Given the limited availability of common resources, decisions regarding possible sets of actions are made dependent on defined community values. In the case where two different planning models exist, the framework advanced here still uses a common resource pool, allowing for tradeoffs between emergency-motivated decisions and sustainability-motivated decisions. Furthermore, community values provide an excellent opportunity for the framework to handle multiple objectives while allocating limited resources.

6.0 APPLICATIONS OF THE SUSTAINABLE DOM PLANNING FRAMEWORK

To illustrate the kinds of issues that can be explored using the proposed DOM planning framework that could not be investigated with previous frameworks, we list two hypothetical examples.

First example: Joplin, MO (Smith & Sutter, 2013)

Joplin, Missouri is considered part of the “tornado alley” due to the high risk of tornados in this part of the country. In 2011, an EF-5 level tornado struck the city resulting in significant loss of life and infrastructure damage. The recovery program emphasized a prompt return to a state of normalcy, and as such, city and state officials did not emphasize or mandate construction policies with higher standards (e.g. building of safe rooms).

Possible scenario: Given the city’s location in a high tornado risk area with expectations for recurrent tornado damages: What happens over the next ten years should two more tornadoes strike? With no mitigation (e.g., no policy mandate for safe rooms or higher building standards, no ecological defenses), costs over a long-term horizon could be high. Would it have been better to consider the cyclical nature of natural hazards over time and include mitigation policies? Should decisions be based on the expected cost over the entire planning horizon?

Second example: New Orleans, LA (Kates, Colten, Laska & Leatherman, 2006)

Over a 288 year history, the city of New Orleans implemented several mitigative projects (e.g., levee construction) to reduce the impact of frequent floods and hurricanes. Inadvertently the over-reliance on a complex network of levees and the resulting "levee-effect" increased New Orleans’s vulnerability to a major 'black-swan' type flood hazard, such as Hurricane Katrina.

Possible Scenario: A city plans for a “black swan” scenario and decides that the risk of not countermanding a possible black swan would result in catastrophic results. The city expends a

significant amount of money, with long-term financial commitments, which could have also been used elsewhere, to cover the longshot possibility of a catastrophic event. In actuality, the black swan never occurs.

7.0 CONCLUSIONS AND FUTURE WORK

This paper proposes a sustainable DOM planning framework, which broadens the typical disaster planning focus both temporally and in terms of planning objectives, additionally emphasizing dimensions external to the disaster event. The implications of the proposed framework lie primarily in shifting the emphasis, as noted in archetypal disaster planning models, from the disaster event to broader and principal issues of long-term community stability, viability and equitability.

While the proposed framework emphasizes the disaster operations context of disaster management, there is need to extend the research to other worthy dimensions of disaster management such as disaster communications, disaster policy, and politics. In particular, in the context of natural hazards, there is need to consider a multi-hazard context inclusive of a hazard's epiphenomenal nature. Moreover, there is also need to apply this framework on the ground and develop appropriate case studies, as well as quantitative models that can support comprehensive disaster planning.

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**CHAPTER 4: LONG-TERM DISASTER OPERATIONS PLANNING
UNDER RECURRENT HAZARDS**

Long-Term Disaster Operations Planning Under Recurrent Hazards

ABSTRACT

It is well recognized that natural disasters are becoming more costly in terms of human life, as well as in their physical, social, and economic impacts, as they increase in frequency and in aggregated effect. Decision science techniques have in the past been shown to advance disaster planning efforts. For example, much progress can be noted in improving short-term recovery operations such as humanitarian logistics. However, limited emphasis has been placed on the long-term development scope of humanitarian operations. In particular, the current application of such techniques, as discussed in the literature, does not provide a comprehensive methodology whereby both mitigation (in advance of the next event) and long-term recovery (following a previous event) are considered contemporaneously in the context of competition for resources over recurrent hazard events. This gap is not only academic; with the increases in disaster effects upon society, decision makers need to be proactive and mitigate against the effects of inevitable future tragedies.

With this in mind, this paper provides a decision approach wherein (1) over a long-term planning horizon (2) both long-term recovery and mitigation are traded off (3) in a manner that allows for the inclusion of humanitarian and social dimensions (as well as fiscal components), and that (4) also enables appropriate stakeholder (community) buy-in and involvement in the planning process.

Keywords: Disaster Operations Management; Humanitarian Operations; Disaster Resilience; Resource Allocation Models; Simulation

Long-Term Disaster Operations Planning Under Recurrent Hazards

1.0 INTRODUCTION AND LITERATURE REVIEW

Not only are the effects of natural hazards costly in terms of human life and physical, social, and economic damages, but also they are increasing in frequency and in aggregated effect. The recent typhoon Haiyan, with estimated recovery costs of close to \$8 Billion, about four million people displaced, and up to fourteen million directly affected (US Congressional Research Service, 2014) is a poignant example of one of these tragedies. In the face of increasing disaster impacts on quality of life and economic support structures, improving the state of the art in decision making associated with planning for and managing disasters has significant implications.

Disaster operations management (DOM) is commonly defined to be “the set of activities that are performed before, during, and after a disaster with the goal of preventing loss of human life, reducing its impact on the economy, and returning to a state of normalcy as disaster operations” (Altay & Green, 2006, pp. 476). Central to the complexity of this concept is its existence as an inherently socio-technical process, consisting of a network of stakeholders working together under possibly conflicting goals who must perform technical activities under temporal externalities. Technical activities associated with DOM are carried out in each of the phases of the disaster management cycle: Preparedness, Response, short-term Recovery (transitional stage between response and long-term recovery), long-term Recovery, and Mitigation.

Activities carried out during the preparedness, response, and short-term recovery phases are temporally motivated around the disaster event (immediately before, during, and immediately

after the event), whereas activities carried out in the latter two phases are focused on the long term. Thus when effecting overall planning for a disaster, managers should not ignore (i) the event-specific actions aimed at short-term emergency response and relief activities, which reflect the importance of alleviating immediate human suffering, or (ii) the long-term actions focused on bringing the community back to a state of normality and viability. Such long-term actions help the community become better prepared for the next disaster event, whenever it happens, reflecting the importance of stability (Holguín-Veras, Pérez, Jaller, Van Wassenhove, & Aros-Vera, 2013) and quality of life issues (Asprone, Prota, & Manfredi, 2014; Turner et al., 2003).

Taking the lead from Anthony (1965), who showed in his early and critical work on management control the ability to and desirability of partitioning the planning process, we note that the DOM planning problem lends itself naturally to hierarchical separation in a similar manner. This is because the formulation and solution can, as a first approximation, be decomposed into (1) an operational/tactical planning model motivated around the disaster event, and (2) a strategic model geared at long-term viability. Hence, these two aspects of the DOM planning problem may be considered independently, as long as an awareness of the other is maintained. In this paper, we shall focus on the second aspect, the strategic model geared toward long-term community viability.

1.1 Disaster Resilience

Over recent years decision scientists have highlighted the unique differences in humanitarian/disaster operations and conventional operations management (Holguin-Veras et al., 2012; Starr & Van Wassenhove, 2014). In particular, researchers have emphasized the need to consider human suffering (Holguin-Veras et al., 2013) instead of the usual measures of cost or benefits. In the context of human suffering, length of recovery is absolutely critical.

One useful measure for this is resilience, as it focuses on a system's coping and recovery capacity for the sole purpose of reducing the time an entity is under stress (Zobel & Khansa, 2012). Resilience as a conventional scientific concept, first used in the 1800's, has its origins in mechanics (Alexander, 2013). The adoption and rapid expansion of the resilience concept outside the physical sciences, however, is due to Holling's (1973) seminal work in ecology. While the historical traditions of resilience are rich with significant contributions from a wide array of disciplines, this has also resulted in a disjointed body of literature in which the definition of resilience is actually a fiercely contested concept (Alexander, 2013; Manyena, 2006; Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008).

The resilience definition that we adopt, consistent with the definition adopted in the decision sciences, as noted in this journal (Zobel and Khansa, 2012; see also Zobel, 2014), is the capacity of a system/community to adapt to an extreme event through a combination of activities geared at absorbing initial impact and subsequent recovery thereafter. The emphasis is on these changes over time and the adaptation that they represent. To measure such resilience, we adopt the engineering-based approach of calculating the area under a time series loss curve as a percentage of the total area T^* available if no loss occurs (Bruneau et al., 2003; Zobel, 2011; Zobel & Khanza, 2012): $R = \left(\int_{t_0}^{t_1} q(t) dt \right) / T^*$, so that $R \in [0,1]$, where $q(t)$ is the time curve being measured, and t_0 and t_1 are the beginning and end points, respectively, over which the measurement is taken.

1.2 Humanitarian and Social Dimensions

The first official US assessments of disasters occurred around 1964 and led, in part, to a conceptual shift from an engineering/structural perspective of disasters to one *more inclusive of human and social dimensions*. This also included a shift from vulnerability models, which

emphasized risk reduction, to resilience models that were more active in placing responsibility of actions/decisions on people, rather than models that simply reacted to nature (Cutter et al., 2008). Important refinements of such models are proposed regularly. For example, recent work by Holguin-Veras et al. (2013) highlights the need to consider objectives that place emphasis on reducing human suffering.

Although human factors are an important aspect of such work, the incorporation of social dimensions into disaster operations management is of little consequence if the community does not “buy in” to the solutions advanced. Moreover, if the solution is to be implemented over the long term, community acceptance of the plan is even more critical. As the literature indicates (Berke, Kartez, & Wenger, 1993; Pearce, 2003), disaster officials often fail to determine and to include community members’ needs in their planning, resulting in a community that does not want to follow, much less embrace, the planned reclamation procedure. An additional goal of this research is thus to show how the community can provide input in two explicit ways: examining policies it wishes included in its planning, and stipulating the measure(s) that should be utilized in evaluating and determining disaster responses. As stated, these policies include both human and social dimensions as well as fiscal components.

1.3 Purpose and Plan of Presentation

The scope of this paper is a focus on humanitarian operations and specifically on the long-term development phases of DOM (mitigation and long-term recovery). This scope is chosen because there is a significant need to widen the focus from relief-driven planning to broader system linkages external to the perturbation when the purpose becomes to emphasize long-term stability and community viability. Moreover, the current state of the literature tends to underplay two aspects of the complexity of disasters. First, research addressing efficiency and long-term

decisions underemphasizes the recurrent nature of hazards and associated events, rather focusing on a reaction to a single epoch (Salmerón & Apte, 2010). A more realistic approach, in the strategic sense, is to address disasters within an explicit horizon or long time window (say 20 or 30 years), thereby allowing inclusion of inter-temporal factors across multiple events (Mileti, 1999; Psaraftis, Tharakan, & Ceder, 1986; Van de Walle & Turoff, 2008). Second, even when dealing with a single disaster event, the literature does not emphasize the importance of modeling both long-term recovery and mitigation in an integrative fashion, as described earlier.

We thus conclude that for purposes of long-term community stability and viability, DOM planning should incorporate these three components, considered together: (1) a community-focused analysis, which (2) provides the assimilation of inter-temporal socio-technical components across a long decision horizon (inevitably accounting for multiple hazards), as well as (3) the integration of long-term planning, accomplished via simultaneous exploration of both mitigation and long-term recovery under constrained resources. Stated differently, the purpose of this paper is to provide a decision approach wherein both recovery and mitigation are traded off throughout a planning horizon in a manner that enables stakeholder (community) buy-in and involvement in the planning process through community-specified policies and community-stipulated measures.

The rest of the paper is organized as follows. The next section (2) develops the basis for our methodological approach. In this section a mathematical programming model is formulated and analyzed under a thousand replications of disaster scenarios generated over a long-term planning horizon. Section 3 provides an enumerative example using an illustrative community (the Portsmouth, VA, USA area under flooding conditions), demonstrating how utilizing the new framework provided in section 2 encourages the community to address important issues in

resilience, being “green,” equity, ensuring economic development, etc. A specific “one-size-fits-all” answer is not provided in this section or this paper; rather multiple runs by planners, based on citizen input, drive the resource allocation model within a feedback loop toward a satisficing solution. Section 4 suggests extending this research into (1) a multi-hazards type of approach advocated by FEMA (FEMA, 1995) and the UN (UN_ISDR, 2005) and (2) a model explicitly incorporating uncertainty, and finally section 5 draws conclusions.

2.0 METHODOLOGY

The methodology proposed for long-term disaster planning consists of a mathematical programming resource allocation planning model responding to a discrete-event simulation model generating disaster scenarios over a long planning horizon. The planning model encapsulates the community’s expressed values.

In order to generate disaster scenarios for analysis by the planning model, we randomly generate one thousand independent 30-year sequences of disasters based on historical community data; “push” those 1,000 replications through all proposed policies one at a time; and then generate outcomes from decisions made by the planning model. Each time the planning model sees a new disaster, it calculates savings from any mitigation in effect, and then it plans future mitigation and recovery efforts from the portfolio of possible projects and recovery strategies the community has listed. Furthermore, upon each instance of any disaster, the planning model bases its analysis on the expected timing and severity of occurrence of the next three expected disasters.

2.1 Planning Model

Critical to the discussion of this paper is the matter of which specific DOM planning issues need community acceptance, as not all of them do (Godschalk, Kaiser, & Berke, 1998; Thomas, 1993,

2012). Thomas (1995, 2012) indicates that in situations where the planning decision is highly technical in nature, public participation would not be effective; however, in situations where public acceptance is fundamental to successful implementation, one should consider how to embrace community inclusion. Both Berke et al. (1993) and Pearce (2003), recognizing that DOM planning decisions have a direct impact on the community, recommend the inclusion of the affected community when discussing issues of goals (assessment criteria). Making the same point, the National Research Council (NRC) (2006) concludes that stakeholder inclusion provides a fundamental mechanism in which the affected community can ascribe varying levels of value across competing objectives.

By having the community specify both objectives and [policy] constraints, we are asking it to specify the following two parts of a resource allocation model.

2.1.1 Specification of Objectives. As noted, the literature prescribes that the affected community should have a say in defining appropriate objectives and assessment criteria; this paper terms these assessment criteria as *community values* (CV). As such, CV represent any value(s) of import to the community, e.g., infrastructure worth, racial and generational equity, economic development, propensity to be ecologically responsible, the tendency to “bounce back” quickly, etc. Moreover, since this paper is focused on long-term planning, we emphasize the performance of the community values over the entire planning horizon using resilience as an appropriate measure.

2.1.2 Specification of Policies. When taking a community focus, however, there is much more to consider than just easily measurable characteristics such as physical damage or monetary loss. As explored in the literature (Cutter, Burton, & Emrich, 2010; Pearce, 2003), a community's assessment of the effectiveness of a recovery policy may depend on more complex factors such

as the fair treatment of underprivileged populations, the length of time that schools are closed, and the availability of shopping and health care. To have a community-focused planning model, therefore, we must somehow take these broader considerations into account.

One way in which community preferences for the outcomes of mitigation or activities can be considered is by examining the effects of *restricting* how resources are reallocated through policy decisions. For example, if a community is concerned about future economic development, then they may wish to consider enacting recovery policies that support this end goal by requiring certain types of investments to be included in any plan. Similarly, if it is concerned about equitable treatment then it may want to consider requiring any proposed mitigation approaches to provide the same level of protection to different socio-economic groups. Because communities may have more than one such issue that is important to them, multiple such policies may need to be considered as part of the overall decision making process in order to explore the range of options that would be most appropriate when assessing the effectiveness of mitigation or recovery activities.

One may implement such a scheme by establishing a suite of representative baseline policies to represent a range of different preferences for possible mitigation or recovery activities. For example, we have constructed seven illustrative policies that may, upon emendation, be considered by a community:

Policy 0 (Do Nothing: Baseline)

With this policy, no recovery, mitigation, etc., are undertaken. This policy is important as a base-line case; it is equivalent in economic decision theory to the “do-nothing alternative,” to which other economic choices should be compared.

Policy 1 (Pure Recovery)

With a pure recovery policy, if a disaster were to occur, resources are expended only on rebuilding and not on mitigating future natural disasters.

Policy 2 (Pure Mitigation)

With this policy all allocated resources are spent only to mitigate against future disasters.

Policy 3 (Economic Development)

The philosophy behind this policy is that by emphasizing recovery on institutions that provide jobs and bring in the most revenue, the community will benefit the most.

Policy 4 (Equitable)

With this policy we insist that the fraction of available resources be expended in each region in proportion to the uninsured damages incurred in that region, appropriately ensuring that all affected members have equal chances of recovery.

Policy 5 (Green)

Under policy 5, the emphasis is on being ecologically sustainable through limitation of projects that change the natural landscape, etc.

Policy 6 (Ceiling Model)

Finally, this policy puts no restrictions on any recovery or mitigation variables except for budget limitations. Thus, no arbitrary constraints are set.

This suite of policies can then be applied to a time-varying DOM model that simulates the impacts of multiple disruptions to explore the relative effectiveness of various policies. The actual set of policies used by a given community may vary from those included in this particular list, but the idea is to capture a range of community values so that their relative effect on the outcomes can be explored in a simple and straightforward manner.

2.2 Resource Allocation Framework

2.2.1 Prior Work. The application of OR/MS models in DOM research tends to be phase specific, particularly aimed at emergency response (Altay & Green, 2006, Galindo & Batta, 2013). More recently though, Edrissi et al. (2013), citing the need for integration across phases, developed an OR/MS model, explicitly considering mitigation, preparedness, and response phases, yet excluding recovery. The model considered specific budgets for actions under each phase, failing to model tradeoffs between the phase decisions, including the long-term ones.

Resource allocation models geared towards more long-term disaster operations are present in the literature. For example, Lund (2002) developed a two-stage linear programming problem formulation to minimize the expected value of costs attributed to flood damages, long-term mitigative options, and emergency response actions. Dodo, Davidson, Xu, and Nozick

(2007) also used a linear model with multiple objectives (minimize risk; minimize mitigation costs) to solve a resource allocation problem in order to decide among different mitigation strategies. Other articles with a similar flavor include: Dodo, Xu, et al. (2005); Vaziri, Davidson, Nozick, & Hosseini (2010); Legg, Davidson, & Nozick, (2012). However, all these models consider a single event rather than modeling over a decision horizon (multi-hazard viewpoint).

Prior work in DOM tends to have models predicated on an isolated hazard event, thereby disregarding the recurrent nature of natural hazards (Salmerón & Apte, 2010). Hazards' recurrent nature needs to be explicitly considered, as Mileti (1999), and Van de Walle and Turoff (2008) note. Godschalk and Salvesen (2004) point to the importance of limiting repetitive disaster damages (e.g., forbidding or buying out resettlements in flood plains). Such modeling has the potential to alleviate suffering and human loss; to position the community more aligned with its social goals; and to reduce cost.

In summary, our work extends the state of the art by explicitly integrating mitigation and long-term recovery in a DOM framework that allows for tradeoffs among the decisions under a long decision horizon. In particular, our work is not limited to a single event; rather we examine multiple events over a specified decision horizon, consistent with the nature of natural hazards.

2.2.2 Resource Allocation Projects

In order to further develop this approach to community-focused decision making, we propose a specific model structure that incorporates both mitigation and recovery planning but yet is general enough to be used with a variety of different community values-focused objective functions. This model utilizes the panoply of possible projects on a community's planning plate that it is considering as potential "mitigators" of future disasters. Projects may range from the small to the large. For example, a community may contemplate a project to place curbing along

a river or a canal; to build an earthen berm, or a low concrete wall. There might be a variation of the previous project that provides a high concrete wall. A further project might suggest buying back (i.e., moving out) houses and property in the floodplain, in particular those structures that repeatedly are “hit” over and over by successive disasters. Another project of a different ilk might involve the relocating of a disaster supply depot.

Note that each of these projects, by the very nature in which communities conduct business, would typically include cost, time, and other resource data. In particular, each project would have at least a total cost, resource requirements, and an associated (projected) mitigation savings. These project data with associated parameters would be included in a Decision Support System’s database, and incorporated in the model discussed below in order to determine project inclusion into the community action plan.

Once “lifeline” [emergency] procedures are completed, recovery will generally proceed in concert with federal and state procedures. However, there is still often some flexibility as to how the local community chooses to proceed. For example, a community’s may choose of a policy from our list of seven will determine what part of town gets “built back” first, or even at all. If a community stipulates that its goal in recovery is the advancement of or provision for economic development (“we’ll recover the businesses along the waterfront first, etc.”), then it is possible that disadvantaged sectors in the community may remain disproportionately unrecovered.

Note that with this framework, the community does not need to specify which policies to consider. Solutions will be determined as to which projects to undertake to maximize specified CVs under *each of the seven* policies. In this manner the community may see how its objectives

“play out” under all policies. This should lead to informed discussion among the stakeholders as to additional runs that should be made before final decisions can be wisely made.

2.3 The Planning Resource Allocation Model

This methodology employs a basic resource-allocation framework, where both long-term mitigation and long-term recovery projects are chosen from among a pool of possible ventures. These projects are allocated resources in order to meet the community’s goals and objectives while implementing community-specified, significant policies. This may generally be written as

Pursue Objective(s) (1a)

subject to: physical constraints (1b)

long-term mitigation project constraints (1c)

long-term recovery project constraints (1d)

policy constraints (1e)

non-negativity, etc. (1f)

The mathematical model here is a disaster planning model for a community over a rolling horizon that incorporates the next three expected disasters. The basic resource allocation problem lies in maximizing community values (CV) in the face of disaster through investment of limited resources into mitigation and recovery decision options. With this resource allocation model, a single community value may be expressed as the objective; *or* the model may easily be written as multiple, (even incommensurate) community values considered lexicographically; *or* multiple (perhaps incommensurate) community values may be combined with community-specified weights, etc., to form the objective. The limited resources are primarily financial and construction-related, and are functions of both time and region, but again, any additional resource constraint that obtains in a particular scenario can and should be included.

Define the following index sets, variables, and parameters:

Index Sets

- i Index of *mitigation* options under consideration
- l Index of *recovery* options under consideration
- j Index of possible *disaster events* over the decision horizon
- k Index of possible *policy options* under consideration
- r Index of *geographic regions* (e.g., census tracts) in the community

Decision Variables

X_{ijk}^M – Level of mitigation strategy option i under policy k for period j in region r . $X_{ijk}^M \in [0,1]$. For example, if $X_{ijk}^M = 0.5$, then apply resources to complete half the project.

X_{ljk}^R – For recovery project l , the decision variable indicates the dollar value of the portion of damage (not covered by insurance) regained during period j in region r , under policy k . $X_{ljk}^R \in \mathcal{R}^+$, where \mathcal{R}^+ indicates the set of real and non-negative numbers.

Objective Variables

Z_r Z captures the community's (measurable) values in region r

N.B.: Z_r may, in general, be a vector; e.g., a community may prescribe infrastructure value as its highest-priority CV and the community resilience as a second-priority Z , etc.

Parameters

Z_r^0 Current/Initial community value in region r

D_r^E Expected damages (amount, in units of CV, as defined) incurred in region r

A_i Damage averted coefficient for mitigation option i , $A_i \in [0,1]$. For example, if mitigation strategy i obviates 25% of the damage otherwise incurred, $A_i = 0.25$

C_{ir}^M Cost coefficient of mitigation option i in region r

L_{jr} Resource limits for disaster period j for the resource under consideration in region r

L_{jr}^U Unused resource limits for disaster period j for the resource under consideration in region r .

K_{jr} Additional resources provided by external agencies for disaster period j in region r ; e.g., insurance monies paid under the National Flood Insurance Program (NFIP). In general, $K_{jr} = f(\text{Incurred damages; \% of citizens in region covered; \% of incurred damages paid})$.

Community Values (CV)

The objective in this model is to maximize community values, where the “CV” is specified by the community, and thus may be *infrastructure value; equity among social classes; preferential treatment for the elderly; or preferential treatment for businesses; measures reflecting safety;*

etc. These various values may be considered either singly; as a group detailed lexicographically; or in weighted combination (with weighting specified by the stakeholders), forming a single objective.

In general, for any vector of community values we stipulate that \mathbf{Z} (the CVs), the variable to be optimized, consists of three terms: the *initial* community value as defined before the study period begins, minus the vector of *damages incurred* (which consists of damages less that component averted by cumulative mitigation actions), plus the *Community Value re-attained* through recovery. Thus we have:

$$\mathbf{Z} = \mathbf{Z}^0 - \mathbf{D} + \mathbf{Z}^r.$$

$$\text{Max } Z = \sum_r \{Z_r^0 - D_r^E [\sum_j (1 - \sum_i A_i \sum_{q=0}^{j-1} X_{iqkr}^M)] + [\sum_j K_{jr} + \sum_l X_{ljkr}^R]\}, \quad (2)$$

where the index r is over geographic regions, i is over mitigation options, and the index l is over recovery options.

Constraints

The basic constraints, by category, are as follows:

$$\text{Resource Constraints} \quad \sum_i C_{ir}^M X_{ijkr}^M + \sum_l X_{ljkr}^R \leq L_{jr} + L_{j-1r}^U \quad \forall j, k, r \quad (3a)$$

$$\text{Flow Constraints} \quad L_{jr} + L_{j-1r}^U = \sum_i (C_{ir}^M X_{ijkr}^M) + \sum_l (X_{ljkr}^R) + L_{jr}^U \quad (3b)$$

$$\text{Strategy Operational Constraints, Mitigation} \quad \sum_j X_{ijkr}^M \leq 1 \quad \forall i, k, r \quad (3c)$$

$$\text{Spatial Constraints, Mitigation} \quad (4a)$$

$$\text{Spatial Constraints, Recovery} \quad (4b)$$

$$\text{Policy Constraints} \quad (5)$$

$$\text{Non-negativity.} \quad (6)$$

2.4 Community Feedback Loop

Figure 1 shows how the resource allocation model fits within the larger planning context necessary. As explained earlier, the first step is to gather from the community both the vector of objective measures it values and any clarification of policies it wishes to state. Next, the

community planners encapsulate the citizens' wishes along with other technical considerations into the mathematical form necessary to specify the initial planning model. Finally, the planners, in the loop at the right of the figure, run the model. As shown with the three concentric ovals, (1) in the innermost oval the planners decipher the model results; (2) they then explain findings to the citizens, detailing ramifications and noting possible issues. [Some appropriate issues, addressed by the model output, are noted in the next paragraph.] The citizens then respond, possibly modifying their initial suggestions. (3) The planners then make necessary adjustments to the model, and the process repeats until a satisfactory plan is achieved. An illustrative example is given in section 3 below.

Some of the issues, ramifications, implications and the tradeoffs between different value schemes addressed by the resource allocation model output under the various policy scenarios include:

- Is it worth doing anything?
- How will the community's value measures of interest (e.g., infrastructure) fare by region over time?
- Are we getting enough back quickly [resilience]?
- How equitable is our planning solution going to be?
- [If appropriate] have we allowed for economic recovery and growth?
- How much 'bang for the buck' are we getting for our resources?
- What if the forecast is incorrect?
- Finally, what policies appear most favorable and in-line with the community's values?

This iterative approach deemphasizes the requirement that *technical* details be understood by the community and reflects the modeling output in terms of relative effectiveness under different

priorities / value systems. The approach can be applied regardless of what performance indicators are used to assess outcomes. So, for example, the standard measures of infrastructure damage or economic loss could be used to compare the outcomes of applying different mitigation and recovery policies in the context of either a focus on sustainable development or a focus on equitable resource allocation. Other, more values-oriented performance indicators could also be chosen, however, such as the number of displaced families at any given point in time. The use of the baseline suite of policies and the issues listed will help the community to examine their relative preference for different approaches.

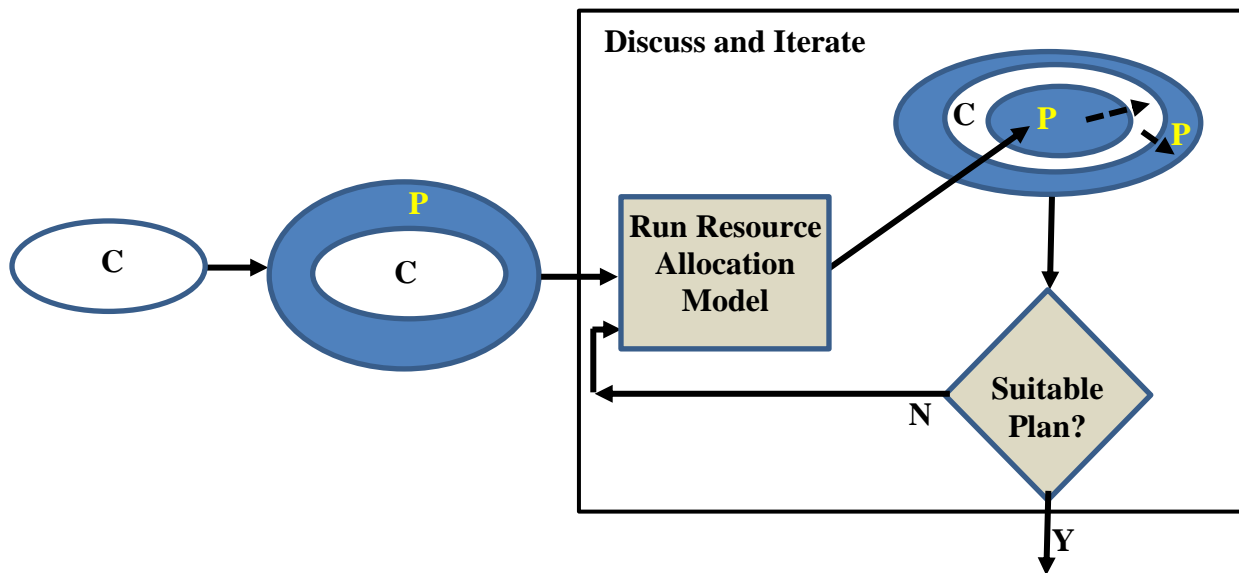


Figure 4-1. Community Input ('C'=>citizenry; 'P'=>planners): Key to the Decision Process

3.0 EXAMPLE

3.1 Example Community

An example is now supplied that illustrates the methodology above for approaching the long-term disaster operations management planning problem in a manner that accounts for the recurrent nature of hazards. The particular type of disaster exemplified is flooding.

3.1.1 Locale. The example is based on some of the natural features of Portsmouth, VA, a community that has been the source of considerable flooding over the past 100 years (City of Portsmouth, 2010; Mitchell, Hershner, Hermann, Schatt, & Eggington, 2013). A Google map rendering of Portsmouth with a FEMA risk-of-flooding overlay is shown in Figure 2; red shading in that figure indicates high-flooding risk areas, whereas pink shading represents regions of moderate flood risk. This figure confirms that Portsmouth is at significant risk from flooding.

Figure 3 shows the Portsmouth area subdivided into four regions. We have defined and differentiated these four regions based on median income and location, as shown in the note in that figure. The figure shows that region 1 is characterized by being in the floodplain; regions 2, 3, and 4 are *not*. Also, note that region 2 does not abut water (although flooding may occur there); hence it makes no sense to mitigate there with sea walls. Finally, we define region 4 (along the waterfront) as the business district, consistent with business density data in Portsmouth.

3.1.2 Initial Community Input: *Objectives and Policies.* As indicated in Figure 1, initial community input is obtained by the planners from the citizenry in a general sense as to preferences and stipulations with regard to objectives and policies. To illustrate the point that the approach advanced in this research may be utilized for practically *any* set of community values postulated, we illustrate the process for four different sets of Community Values (CVs) for Portsmouth.

The first (and primary) set of Portsmouth CVs we defined are as follows; note that this set is (deliberately) chosen to consist of incommensurate measures. In somewhat traditional fashion, the first community value Z^1 is set to be the dollar value of Portsmouth's infrastructure. When flooding damage occurs, the model uses eq. (1) to reduce the community value Z^1_r in each

region by the amount of infrastructure damage incurred within the region. The amount of damage, of course, is alleviated by any mitigation policies put in place prior to the flooding. Moreover, this community value will increase subsequent to damage by all recovery policies in place and from National Floodplain Insurance Program payouts (which vary by region).

The second CV we specify in the first set is resilience (see Bruneau et al., 2003, Zobel, 2011), an indication of a community's ability to bounce back from a disaster. In this first of the four cases, it is specified that once the first CV measure (infrastructure) is maximized, the model should then be re-solved so that resilience is maximized, given that the first CV measure is not degraded.

The three other Community Value sets we solved in this example are “variations on the theme” of the values “infrastructure” and “resilience.” The second set consisted of the single objective function “*Max Infrastructure.*” The third set was to maximize a weighted combination of the two values, namely, “ $\text{Max } \{(0.7 * \text{Infrastructure value}) + (0.3 * \text{Resilience value})\}$.” And the fourth objective was to “Max the Resilience value, then to Max the Infrastructure value – lexicographically.”

Again we note that, although in the preceding discussion we chose resilience and infrastructure to illustrate the planning model, any combination of social, economic, technical, etc., measures that the community values may be employed.

For each of the four cases, the appropriate set of CVs takes its place in equation (1a).

All seven policies (baseline; pure recovery; pure mitigation; economic development; equitability; being “green;” unrestricted ceiling) mentioned in section 2.1.2 are included. In this example, two projects are considered for mitigation (equations (1c)): building sea walls in regions 1, 3, and 4 (there is no water in region 2), and buying back homes and property that lie in

the floodplain (region 1 – see Figure 2.) For economic development (policy 3), the business district (region 4) is guaranteed to receive at least 50% of the total resources available for the current disaster; these funds may be spent on either mitigation or recovery. Under the equitability policy (#4), the fraction of available resources expended in each region must be proportional to the uninsured damages incurred in that region. Finally, with the green policy, upon a disaster, at least 50% of the floodplain must be bought back, and as part of being ecologically sustainable includes an emphasis on not altering the natural landscape, no funds can be expended on sea walls. The mathematical formulation for each policy as applied to Portsmouth is given in Appendix II. These policy equations are entered into the resource allocation model as equations (1e).

As indicated in Figure 1, citizenry input is processed by the planners and reconstituted technically so it may be included in the resource allocation model. Again, it should be noted that the point here is not that the community has expressed a preference for one policy over the other, but rather that each of the seven policies adapted to Portsmouth is formulated and will be considered by being run through the resource allocation model for each of the four defined regions with the specific community values indicated above incorporated.

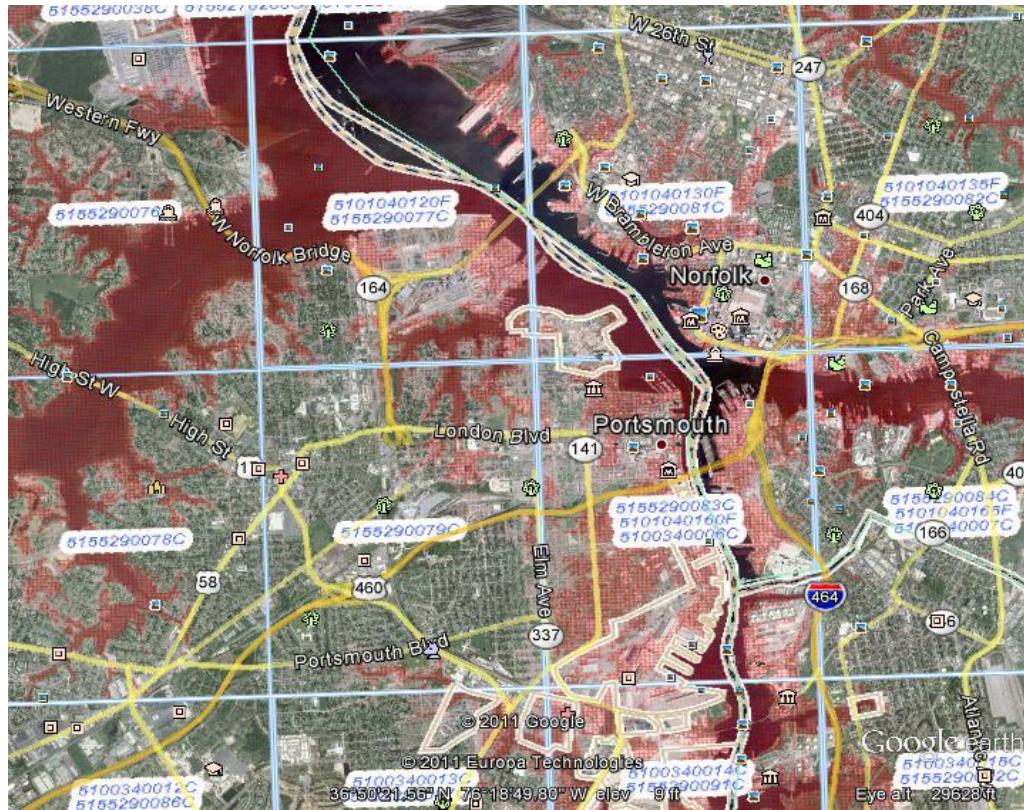
3.1.3 Weather Input: *Flooding IATs and Severity.* With the planning model specified in terms of its two-measure CV, its constraints, and the portfolio of seven initial possible policies, it remains to generate sequences of disasters to be run through the model. In particular, we randomly generate one thousand independent 30-year sequences of disasters based on historical Portsmouth data; “push” those 1,000 replications through all seven policies one at a time; and then generate outcomes from decisions made by the planning model. Recall that each time the planning model sees a new disaster, it calculates savings from any mitigation in effect, and then

it plans future mitigation and recovery efforts from the portfolio of possible projects and recovery strategies the community has listed. Also recall that upon each instance of any disaster, the planning model bases its analysis on the timing and severity of occurrence of the next three expected disasters.

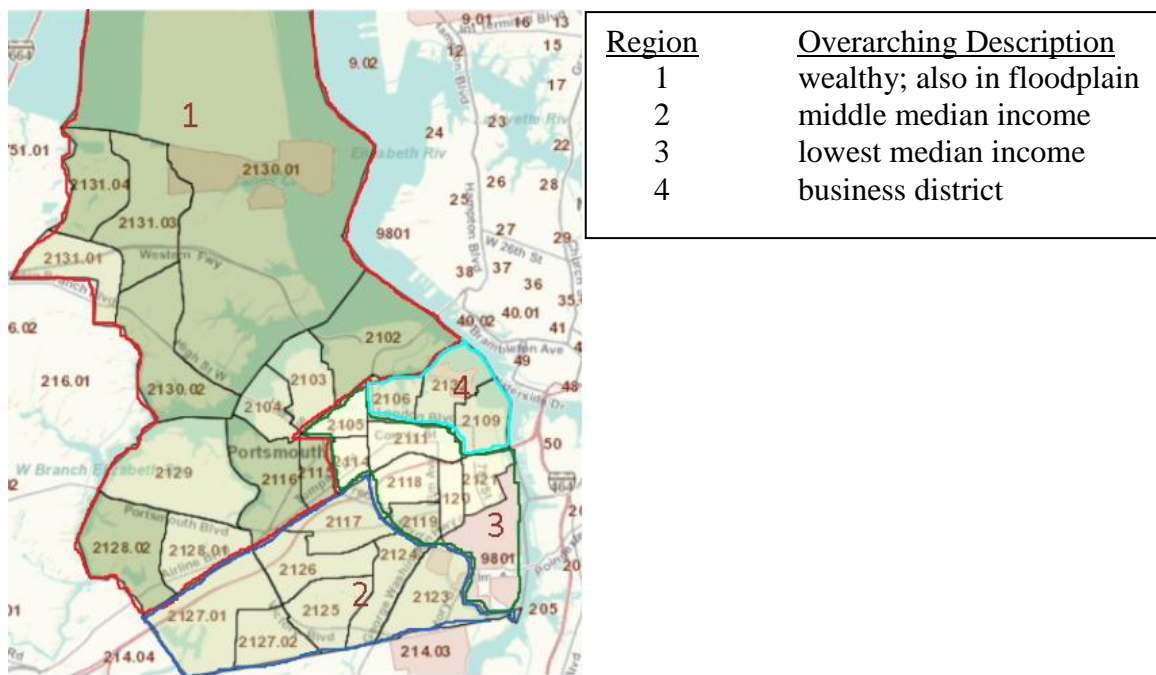
For the disasters to be faced by Portsmouth in our example setup, we generated the inter-arrival times and severity of storm damage from data we collected from Mitchell et al. [2013], reflecting Portsmouth's history of storm damage. To demonstrate the capability to model different types of disasters, we classified Portsmouth storms into two *types*. The first storm type consisted of tropical storms, Nor'easters, and category 1 and 2 hurricanes, whereas the second was category 3 and higher hurricanes. Based on historical storm data for the past 100 years, we fit triangular distributions for both severity and inter-arrival times for each type of storm, where we generated parameters representing the most likely, the smallest, and the largest values occurring.

3.2 Example Community Resource Allocation Model

Following the flow of Figure 1, the initial resource allocation model for Portsmouth (equations 1(a) through 1(f)) is formulated. Additional details (e.g., parameter values, etc.) are listed in Appendix I for the interested reader.



Google Earth, version 7; Flooding Risk Overlay provided by FEMA’s “Stay Dry,” version 3.
Figure 4-2. Google Map Image of Portsmouth, VA, with a Flood Hazard Overlay



(Source: U.S. Census Bureau, 2006-2010 American Community Survey)

Figure 4-3. The Four Defined Portsmouth, VA, Regions

3.3 Initial Results

As indicated in the “Discuss and Iterate” block in Figure 1, the planners (at the center of the three-layered oval) examine results from running the Decision Support System, which in turn evaluates each of seven policies 1000 times.

3.3.1 Planners’ Analysis of Initial Results. The planners first examine *Policy 0* (the ‘Do-Nothing’ Alternative) results to see if it is worth pursuing any policy in Portsmouth. If the community is short-sighted in its purview, for example wanting results within 5-10 years, in the case examined here almost no benefit of policy implementation will be seen. For example, the “Green” policy indicates that the median infrastructure CV does not show any payback over the ‘do-nothing’ alternative for six years. A longer-run perspective, however, is more promising; for instance, the Green policy suggests that starting with year 6 infrastructure is restored almost linearly at a significant rate of \$280K per year.

The question *how did the community’s value measures of interest (infrastructure and resilience) fare by region over time* begins to show a few problems with several of the policies as presently defined. As seen in the snapshot of one run in Figure 4a for the *Economic Development* policy, the business community shows an *increase* of about 12% over the life of the study, whereas the other regions (1, 2, and 3) decline in value by roughly 15, 35, and 15 percent, respectively. Recall that region 2 encompasses the middle median income citizens; they are unlikely to be ‘happy’ with these results. Figure 4b points out that the business community (region 4) bounces back the most quickly from the disasters facing the city, and in fact never has a resilience below 100%. That region ends being slightly more resilient than its initial value. Conversely, all three other regions drop in resilience by about 15% - 20% ultimately, dropping below 100% after three years and never recovering. Figure 4 clearly shows that there is not

equity across the four Portsmouth regions for the solution graphed. In fact, this analysis practically advocates that additional variables reflecting community concerns and values, for example impact on the elderly and by race, may also be necessary and should be discussed with the community at large.

The planners may additionally (with the results generated) discuss whether the current plan allows for economic growth and recovery. Further plots (not shown) reinforce the notion of Figure 4 that the business community is being well cared for.

Planners may also address the matter of how much ‘bang for the buck’ the community is getting for its resources. Stated differently, should the community attempt to get more resources? Should resources be shifted (if possible) among categories? Should more resources be pursued now? The DSS defines an efficiency index as the ratio of *(Policy Solution – Do Nothing Policy Solution) / Total Resources Consumed*. In this case the index is merely the infrastructure value determined from a policy solution, adjusted to account for the opportunity cost (doing nothing), divided by the planned resources expended – a so-called ‘bang for the buck.’ Plots of this index show that initially (with \$1M planned expenditure per disaster) the efficiency is 2.58, whereas if we procure additional resources so that we double our expenditures per expected disaster, the efficiency *drops* to 2.2. By decreasing the expected resources expended per disaster to 0.75 units scale, the efficiency index *increases* to 2.63. This does not mean that if we decrease our resource level, we will have a better terminal infrastructure value than if we do not; rather, it says we will get more ‘bang for each buck’ that we spend at the lower resource level.

Finally, the planners ask themselves, *what if the forecast is incorrect?* In particular, *what if the IAT (inter-arrival time) of disasters is different than planned [either shorter or longer]?*

What if the severity is amplified or attenuated? Figure 5 notes the Green infrastructure results across all objectives and all policies. (The Green policy is essentially tied as best policy under present conditions.) These graphs show the uncertainty across 1,000 possible simulated disasters *if the forecast is correct*. [The tick marks indicate the 90th-percentile of values as well as the complete observed range obtained.] The figure shows that at the conclusion of the planning horizon, there is considerable variability in replication infrastructure values – including some possible ‘black swan’ events. Of course, if the forecast is *incorrect* in the sense of the expected time between disasters, even preferred policies may change. Furthermore, the forecast may be wrong in that the severity of storms is misestimated. Nonetheless, the planners have gathered some information from the initial set of DSS runs informing the range of uncertainty that may be faced by Plymouth.

3.3.2 Soliciting Additional Community Feedback. Returning to Figure 1, the planners present to the community in non-technical terms the results of their initial analysis. Items presented in this case (indicated by the ‘C’ in the middle region) might include the initial delay in payback to be expected; the inequity by region – including the favorability to the business district and the ‘hit’ to be taken by the middle class (region 2); the viability of economic growth and development in the face of flooding; and some indication of the possible range of expected outcomes given forecast uncertainty. Planners should then solicit feedback from the community with respect to these issues.

3.3.3 Re-running the Model and either Terminating or Iterating. Finally, with respect to the outermost region of the oval in Figure 1, the planners incorporate feedback and re-run the models. Depending on results, the process either repeats with additional feedback, or it terminates with a plan that has community buy-in.

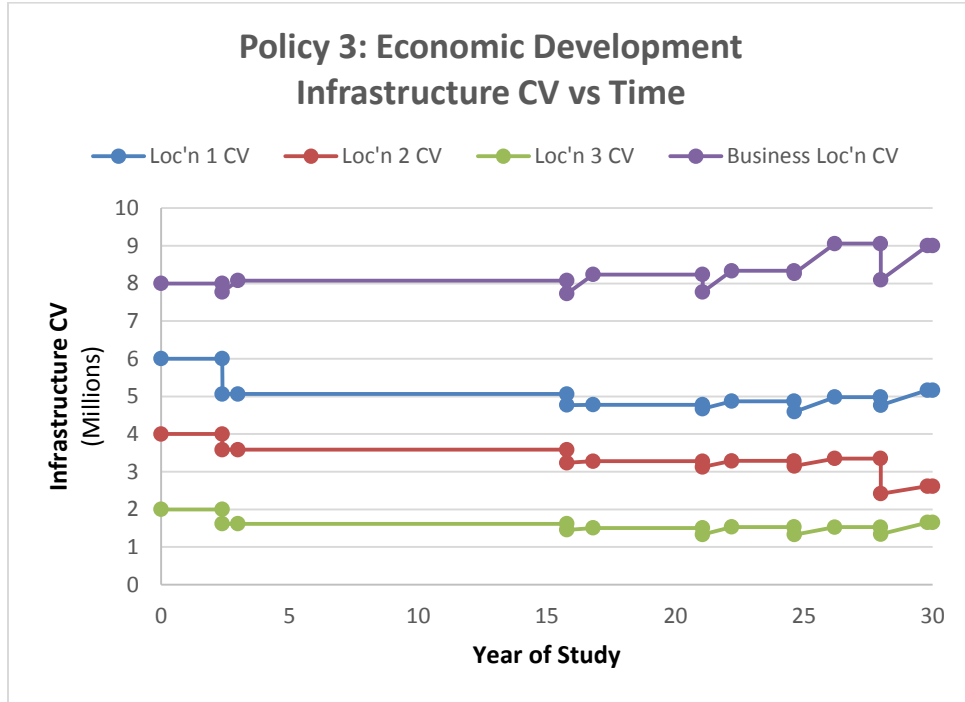


Fig. 4-4a. Infrastructure Community Value vs. Time for All Four Regions under One Policy

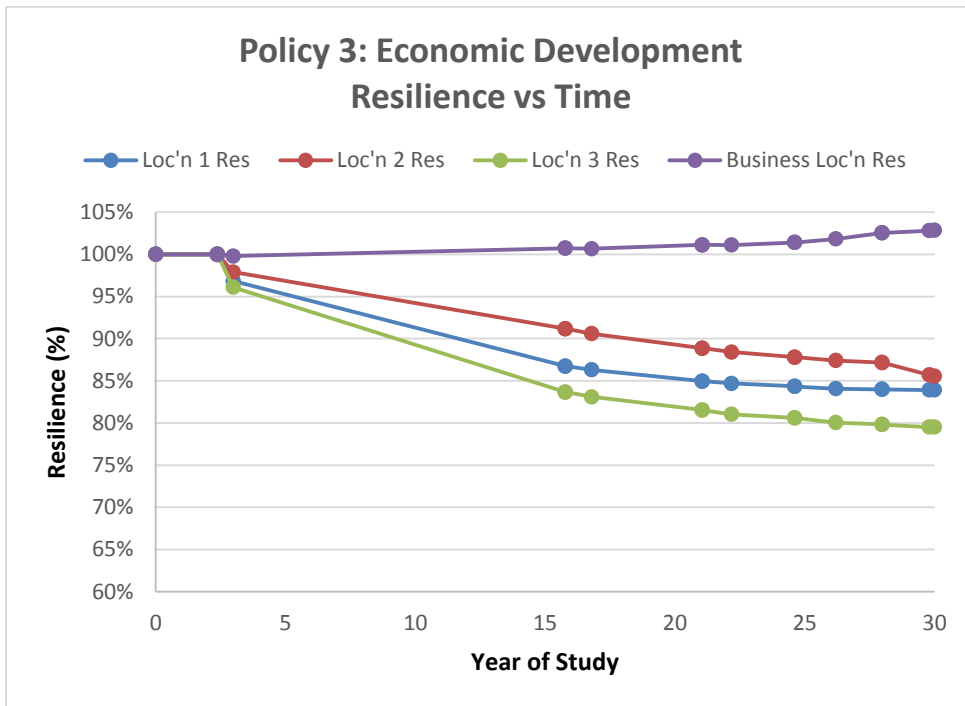


Fig. 4-4b. Resilience Community Value vs. Time for All Four Regions under One Policy

Figure 4-4. Single Replication Showing Both Community Values over Time for One Policy

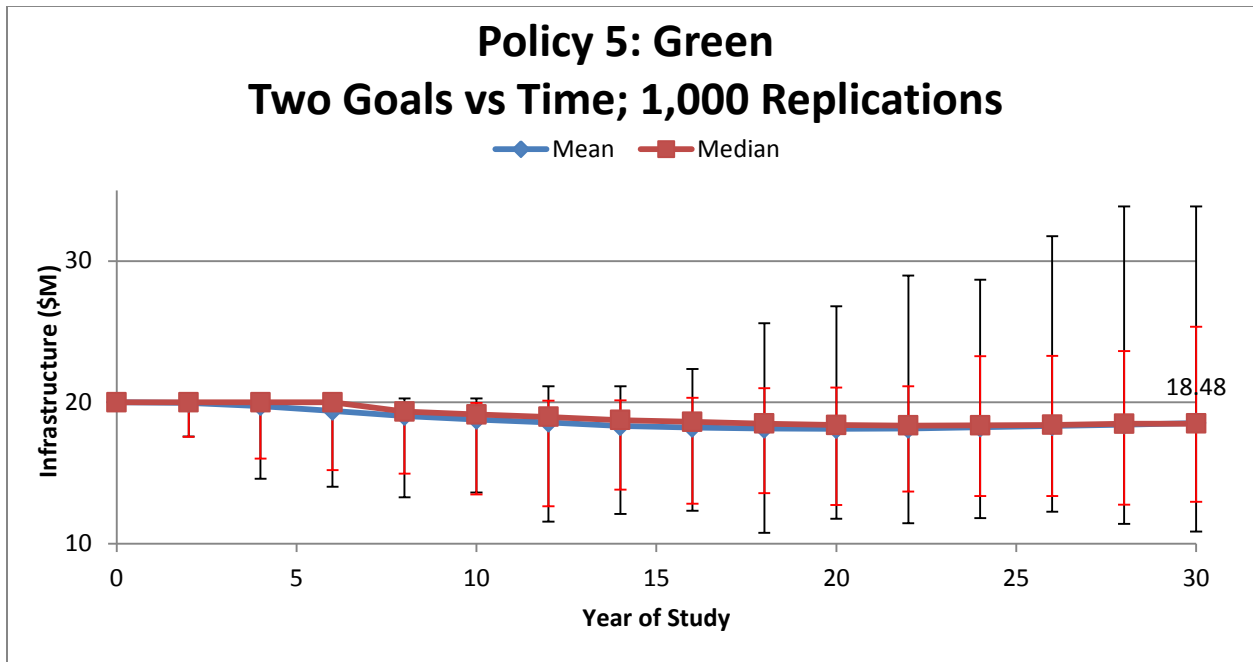


Figure 4-5. Variations of the Green Policy Under max Infrastructure Criterion (Goal 1), then a Max Resilience Criterion (Goal 2)

4.0 EXTENSIONS

The work reported in this research is currently being extended by the authors in two major directions. The first is to extend the single-disaster framework reported here into what FEMA refers to as an “all-hazards” [actually, multi-hazard] analysis whereby synergies and dependencies among disasters are incorporated in the planning process. The second addition is the development of an explicit uncertainty analysis, in which resource, payoff, cost, etc., data are described non-deterministically. So-called “black-swan” events are also included.

5.0 CONCLUSIONS

This research has demonstrated a decision approach wherein the long-term planning aspect of disaster operations management considers both the recovery and the mitigation phases together over a multi-epoch planning horizon. This is critical as both the frequency and impact of natural hazards is increasing dramatically; failure to mitigate effectively over multiple occurrences of a disaster event can result in increased loss of life as well as be costly in social and economic terms. The decision approach advanced here provides data informing answers to multiple, general questions, from which the community then must engage in open, informed discussion, considering interactively-determined tradeoffs, before it specifies its recommended course of action to upcoming disasters.

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APPENDIX A: Specific Values in the Resource Allocation Example for Portsmouth, VA

Index Sets

- i Index of *mitigation* options under consideration; $i = \{1, 2\}$
 Mitigation option 1: *build sea walls*
 Mitigation option 2: *do not allow construction in the floodplain*
- l Index of *recovery* rebuilding options under consideration; $l = \{1\}$
- j Index of possible *disaster events* over the horizon
- k Index of possible *policy options* under consideration; $k = \{0, 1, 2, \dots, 6\}$
- r Index of *geographic regions* (e.g., census tracts) in the community; $r = \{1, 2, 3, 4\}$

Parameters

- L_{jr} Resource limits (\$K) for disaster period j for the resource under consideration in region r
 $\sum_{r=1}^4 L_{jr} = 1000, \forall j;$
- K_{jr} Recovery attributed to insurance monies paid, a function of (a) incurred disaster damages; (b) whether NFIP insurance has been obtained by the community as a whole; and (c) the percentage of individuals in region r actually covered by NFIP insurance.

Parameters	Value
Z_r^0 (in \$M)	$Z_1^0=6; Z_2^0=4; Z_3^0=2; Z_4^0=8$
A_i	$A_1=0.2; A_2=0.4$
C_{ir}^M	$C_{1r}^M=200; C_{2r}^M=500$

Constraints

Spatial Constraints, Mitigation

Since region 2 does not abut water, no sea walls can be placed there (mitigation strategy $i = 1$); i.e., $X^M_{1jk2} = 0, \forall j$ disaster events and all k policies. (A-1a)

Also, regions 2, 3, and 4 are *not* in the floodplain, therefore buying back property in these regions as a mitigation strategy ($i = 2$) is never pursued regardless of policy choice;

$X^M_{2jk2} = X^M_{2jk3} = X^M_{2jk4} = 0, \forall j$ disaster events and all policies k . (A-1b)

Spatial Constraints, Recovery

[None for this example.]

NFIP Coverage (K_{jr}) for region r during disaster j .

The city of Portsmouth *does* have NFIP insurance for all future disasters j , i.e., it has met the necessary building standards, etc., required by the federal government, and has thus made its citizens eligible for NFIP insurance. Hence individuals in Portsmouth are able to individually purchase this insurance to cover their private property. It is assumed for this example that anyone purchasing this insurance will be paid 80% of their disaster-damage amount and that the percentage of individuals purchasing NFIP insurance, by region, is as follows:

Percent of Individuals Purchasing NFIP Insurance			
Region 1	Region 2	Region 3	Region 4
80%	50%	20%	90%

APPENDIX B: Policy Constraints for Portsmouth, VA

Policy 0 (Do Nothing: Base-line) (k = 0)

In this case, *all* mitigation and recovery decision variables are set to 0, namely

$$X^M_{1j0r} = X^M_{2j0r} = X^R_{1j0r} = 0, \forall j \text{ disaster events}; r = \{1, 2, 3, 4\}. \quad (\text{B-1})$$

Policy 1 (Pure Recovery) (k=1)

With pure recovery, the mitigation variables are set identically to zero, while the recovery variables are allowed to range between 0 and any non-negative number.

$$X^M_{1j1r} = X^M_{2j1r} = 0, \forall j \text{ disaster events}; r = \{1, 2, 3, 4\}. \quad (\text{B-2})$$

Policy 2 (Pure Mitigation) (k=2)

With pure mitigation, the recovery variables are set identically to zero, while mitigation variables are allowed to range between [0.0, 1.0].

$$X^R_{1j2r} = 0, \forall j \text{ disaster events}; r = \{1, 2, 3, 4\}. \quad (\text{B-3})$$

Spatial constraint (AI-2a) is imposed here, which says sea walls cannot be built where there is no water (namely, *in region 2*).

Moreover, spatial constraint (AI-2b) is enforced with this policy, as the flood-plain cannot be bought back where there is no floodplain (i.e., in regions 2, 3, and 4).

Policy 3 (Economic Development) (k=3)

With this policy, the business district (region 4) is guaranteed to receive at least 50% of the total resources available for the current disaster; these funds can be spent on either mitigation or recovery:

$$\sum_{i=1}^2 C_{i4}^M X_{ij34}^M + \sum_{l=1}^1 X_{lj34}^R \geq 0.5 * \sum_r (L_{jr} + L_{j-1r}^U) \quad \forall j. \quad (\text{B-4})$$

Policy 4 (Equitability) (k=4)

With this policy, it is insisted, due to equitability, that the fraction of available resources expended in each region must be proportional to the uninsured damages incurred in that region.

Thus, other than restrictions due to spatial constraints, the fraction of resources expended in each region must be proportional to the damage incurred there:

$$\text{Let } L_j^{Tot} = \sum_r L_{jr} \quad \forall j.$$

Further, define

D_{jr}^u as the *uninsured* damage incurred in region r due to natural event j , and

$$L_{jr}^{fraction} = \left(\frac{D_{jr}^u}{\sum_{r=1}^4 D_{jr}^u} \right) L_j^{Tot} \quad \forall j, r.$$

Then equations (AI-1a) and (AI-1b) are rewritten as follows for this policy:

$$\sum_{i=1}^2 C_{ij4r}^M X_{ij4r}^M + \sum_{l=1}^1 X_{lj4r}^R \leq L_{jr}^{fraction} \quad \forall j, r. \quad (\text{B-5})$$

Policy 5 (Green) (k=5)

Under policy 5, to be green and reduce recurrent damages, as much money as possible is invested into floodplain buyback and into recovery. In particular, it is insisted that at least **50%** of the floodplain be bought back. Additionally, as part of being ecologically sustainable includes an emphasis on not altering the natural landscape, money is not expended on sea walls. Therefore, other than restrictions due to spatial constraints:

$$\circ \text{ floodplain buyback in region 1 is encouraged } (\sum_{j=0}^3 X_{2j51}^M \geq 0.5), \text{ and} \quad (\text{B-6a})$$

$$\circ \text{ recovery in all regions is also supported } (X_{lj5r}^R \geq 0, \forall r). \quad (\text{B-6b})$$

- sea walls are expressly prohibited, namely

$$X^M_{ljsr} = 0, \forall r, j. \quad (\text{B-6c})$$

Policy 6 (Ceiling Model) (k=6)

With the final policy, no constraints (beyond resource constraints) are placed on any mitigation or recovery variable other than the stipulation that each must lie within the range [0.0, 1.0].

Non-negativity

$$X^M_{ijk} \geq 0 \quad \forall i, j, k, r \quad (\text{B-7a})$$

$$X^R_{ljk} \geq 0 \quad \forall l, j, k, r. \quad (\text{B-7b})$$

CHAPTER 5: DECISION SUPPORT FOR MULTI-HAZARD DISASTER PLANNING

DECISION SUPPORT FOR MULTI-HAZARD DISASTER PLANNING

ABSTRACT

This research begins the discussion of how to fill a significant gap in the disaster planning literature. The work proposed in this paper extends the current work carried out in analytical modeling of disaster planning, in two main ways: (1) by including multiple disaster types and the various interactions that arise, and (2) by considering a long-term decision horizon to capture multiple event occurrences under implementation of both mitigation and recovery intervention strategies. To address this need we propose a Decision Support System (DSS) that allows stakeholders to investigate the effects of their disaster planning across a range of potential sequences of hazards, a priori, in the most complete manner proposed to date. An example taken from Mombasa, Kenya, is supplied to pedagogically illustrate concepts.

Keywords: Decision Support, Disaster Planning, Multi-hazard Disaster Management

DECISION SUPPORT FOR MULTI-HAZARD DISASTER PLANNING

1.0 INTRODUCTION

More than a few regions of the world are cradles of conditions that spawn complex disasters. For example, Kenya's second largest city, Mombasa, a region of interest to the authors, is a tourist destination that is critical to the Kenyan national economy. As the largest international seaport in East Africa, many east and central African countries rely on the Mombasa port for access to various goods, raw materials, critical machine parts, humanitarian supplies, etc. Mombasa's geopolitical characteristics, its central role in regional trade, and recent military forays by Kenya into neighboring Somalia make it vulnerable to *multiple* disasters, including terror attacks (Botha, 2014), and natural hazards such as floods (Kebede et al., 2012), tsunamis (Ngunjiri, 2007; Odhiambo, 2009), droughts (Awour et al., 2008), and famines (Awour et al., 2008). Additionally, Mombasa is a heavily populated urban center, and when disasters do occur there, they often cause significant consequences.

Unsustainable practices such as illegal logging of acacia trees are driven by the demand for charcoal, a primary energy source for cooking and heating in sub-Saharan Africa; for example over 43% of Kenyans and 50% of Somalis use charcoal as a primary energy source for cooking and heating (Dalberg, 2012). Such ill-fated practices affect vast acreage of natural woodlands and bush lands resulting in significant deforestation (Dalberg, 2012) and consequently in increased susceptibility to extreme events such as floods (Parry et al., 2012) with serious consequences. Current estimates suggest that a 1-in-100 year flooding event in Mombasa would result in close to 190,000 people affected and US\$470 million worth of assets exposed (Kebede et al., 2012). Perhaps surprisingly to the reader not completely familiar with East

African politics, the charcoal industry has provided a significant opportunity for Somalia's terrorist group al-Shabaab to charge a "safe-passage" fee for the shipment of charcoal, thereby generating millions of dollars - a significant fraction of that organization's operating income (UNEP, 2014). Over the last three years in particular, al-Shabaab (now allied with al Qaeda) has become a significant terrorist threat in Kenya, the most notable being the Westgate Mall bombing in 2013.

The situation in Mombasa, Kenya is typical in many ways in the sense of being home to multiple, complex disasters. Starr and Van Wassenhove observe that the interactions between various extreme conditions make resulting disasters quite complex, noting that a small crisis like a poor harvest can result in long-term famine, political upheaval and conflicts, a refugee crisis, and so on (Starr & Van Wassenhove, 2014). Moreover, many regions in the world are vulnerable to more than one type of hazard (Kappes, Keiler, Elverfeldt, & Glade, 2012). Consequently, traditional disaster planning models motivated around a single hazard in isolation are inadequate in many cases. Typhoon Haiyan was a recent example of this where, beyond the monstrous physical damage caused, additional secondary hazards including social unrest and disease outbreaks widely affected the stricken area. This situation can only be expected to worsen given the context of climate change and the increased frequency of weather extremes projected over coming decades.

1.1 The Inadequacy of Single-Hazard Modeling

The inadequacies in single hazard modeling can be encapsulated by two fundamental issues: the inherent nature of communal safety and the nature of hazards. First, populaces are concerned inherently with comprehensive safety encompassing the entire range of hazards that may pose a risk to them (Pollet & Cummins, 2009; Basher, 2006). For example, an urban city center such as

San Francisco, CA with a population close to 850,000 is at risk from wild fires, tsunamis, landslides, earthquakes, flooding, heat waves, and droughts (Ayyub, 2013). The second source of incongruence, linked to the nature of hazards, is captured in typical analytical planning models that fail to consider the epiphenomenal (Zhang et al, 2012) and recurrent (Salmeron & Apte, 2010) nature of the hazards they model.

Institutions such as FEMA (FEMA, 1995) and the UN (UN_ISDR, 2005) have encouraged the use of a “multi-hazard” approach to risk analysis and assessment. Multi-hazard refers to “relevant hazards,” not necessarily all hazards, as defined by the concerned entity. For example, the European commission defines relevant hazards in their guidelines for risk assessment as those that exceed the following thresholds: More than 50 persons are affected and economic and ecological costs greater than one million Euros (Kappes et al., 2012)). Significant synergistic benefits can be achieved by taking a multi-hazards perspective. For example, substantial economic and outcome efficiencies can be gained during the planning process (Pollet, 2009). Additionally, better and more accurate risk assessments result in apposite disaster planning decisions (Cox, 2009; Marzocchi et al., 2012; Selva et al., 2013).

1.2 Shifting the Emphasis from Humanitarian Relief to Community-Led Recovery

The ascendant research perspective in the disaster operations field has been that of the humanitarian organization (service provider) as the decision maker (humanitarian operations); this is amply evidenced by research published in the top OM journals (such as *POM* and *JOM*). As a consequence, the humanitarian operations field has focused on addressing problems specific to this paradigm. For example, much research has focused on humanitarian logistics mostly in the disaster relief phase (Salmeron & Apte, 2010; Holguin-Veras et al., 2012; Holguin-Veras et al 2013; McCoy & Lee, 2014) with several studies concerned with the development phase

(Kreustchmer et al., 2014; Eftekhar et al., 2014), addressing those challenges specific to humanitarian organizations. This perspective has been critical to the development of the field as we know it; however, a significant voice is lacking in this discussion: the affected community, which in fact is critical to the *sustainability* of development-oriented programs (Kreistchmer et al., 2014).

The current paradigm, with the humanitarian organization as the decision maker, understandably positions power in the hands of the donor and not the beneficiary. As a result, the community's input is often neither modeled nor acknowledged. If the disaster management solution is to be implemented over the long term (as we consider here), community acceptance of the plan is even more critical. As the literature indicates (Berke, Kartez, & Wenger, 1993; Pearce, 2003; Thomas, 2012), disaster officials often fail to determine and to include community members' needs in their planning, resulting in a community that does not want to follow, much less embrace, the planned reclamation procedure.

Starr and Van Wassenhove (2014) note that the humanitarian operations field is dynamic and that "profound changes are expected in the future;" in particular, they highlight the importance of expanding the nature of the humanitarian operations domain. The research that has been done to date is important and even critical; nonetheless, it is now necessary to expand the view to a longer range, broader community-focused, more sustainable view that encompasses multi-hazard thinking.

1.3 Purpose, Scope, and Plan of Presentation

The purpose of this paper is to provide a first-step in multi-hazard analysis, which accounts for multi-hazard interactions, optimizes community-specified values over the long-term, and includes both recovery and mitigation considerations. In particular, this research (1) highlights

and includes the unique features in disaster operations management (DOM) modeling arising from dependency relationships under multi-hazards; (2) proposes a generalized mathematical model including both mitigation and recovery for DOM multi-hazard planning over the long term; and (3) provides an illustrative example.

The next section of this paper (2.0) offers a literature review on multi-hazards and disaster management in that context. Section 3.0 presents the methodology utilized, including a presentation of the mathematical planning model. Section 4.0 contains a pedagogical example illustrating the key features of the model by way of three hazards, as noted in the literature as concerns for Mombasa, Kenya. Section 5 contains discussion, and the last section summarizes and concludes.

2.0 LITERATURE REVIEW

Recent disasters in the Philippines and New York have highlighted the insufficiency of traditional disaster planning models motivated around a single risk source. Moreover, recent literature in natural hazards has emphasized the importance of a multi-hazard approach to disaster management beyond the simplistic addition of individual disasters (Kappes et al., 2012; Schmidt et al., 2011). Therefore in this research we focus upon a multi-hazard approach to disaster operations management (DOM) with an emphasis on the longer-term phases of DOM (mitigation and long-term recovery).

2.1 Definitions and Types of Multi-Hazard Management

In this paper hazard is defined as an extreme event with potential damaging consequences (Ayyub, 2012; Kappes et al., 2012). In particular, we focus on hazards that result in disasters (i.e., they exceed the capacity of the affected community to respond to it in such a way as to save

lives, to preserve property, and to maintain the social, ecological, economic, and political stability of the affected community (Pearce, 2000)).

Multi-hazard management refers to the management of a “whole range of ... hazards that pose a risk to humans, assets, and communities” (Kappes et al., 2012 p. 1926). The approach does not mean planning for all types of disasters. It does mean that its emphasis is on seeking the commonalities that exist in likely hazards and using that information and sets of relationships to plan better (Waugh, 2005).

Hazards can manifest themselves at many different spatial scales, from a localized chemical spill to a nationwide drought. In this work, we focus on hazards whose impacts are felt at the regional level (Greiving, 2006; Hewitt and Burton, 1971). Such hazards may therefore impact multiple communities with different demographic and geographic characteristics. Although hazards affect almost all societal elements, it is critical infrastructure assets that are often identified as being most important to protect against these impacts. Such assets can include roads, utility networks, etc. Similarly, hazards can be analyzed under different topological scales. In this work, we focus on the consideration of a range of likely hazards that affect a region, and the hazards' possible interactions with each other. Specifically, this paper considers all the following: independent hazards, independent hazards that happen to occur simultaneously, and the epiphenomenal consequences of hazards.

2.2 Benefits of a Multi-Hazard Approach

The literature lists several benefits of a multi-hazard approach to disaster management. The first benefit of a well-thought-through approach to multi-hazard disaster management is that it enables readiness and preparation against multiple singular eventualities. For example, in an editorial in *Natural Hazards Review*, Scawthorne et al. (2006) emphasize that it is “recognized

that the mitigation of one natural hazard in isolation is not efficient – a multi-hazard approach is required.” In this regard Peterson and Truver (2006) cite the case of the United States Coast Guard. The U.S. Coast Guard is responsible for 95,000 miles of navigable waterways wherein they plan their resource utilization such that the same resources secure against multiple threats – aid in natural hazard management (Hurricane Katrina), drug trafficking, and protection of the U.S. coasts. For example, the same boats and individuals can patrol against drugs, rescue individuals, and help guard against improper immigration.

The second benefit of such an approach is that it allows for an efficient or optimal allocation of limited funds. This is true in at least two senses. First, as Kappes et al. (2012) note, multi-hazard management necessitates the management of multiple hazards, their interactions and dependencies rather than the management of single threats in isolation. For example, if a community plans for two possible disasters independently, considering them as the sum of single hazard risks, then funds may be expended inefficiently; whereas when allocating based on consideration of the complete risk package (including interactions), synergies may be taken advantage of, thereby generating a more beneficial overall response.

Second, the literature points out the danger in limited budget situations of techniques such as risk prioritization, in which resources are allocated to a priority ordered list of individual risks (Cox, 2009). The example of Table 5-1 makes this point succinctly.

With prioritized risks, a budget of \$19,000 implies only projects 1 and 2 may be undertaken, thereby averting a risk of 16 units. But note that a better choice is to pick projects 1, 3, and 4, thereby averting 19 units in risk – still within the budget. Under the realistic assumption of limited resources, risk prioritization therefore may not be appropriate.

Table 5-1. Risk and Benefits of Candidate Projects

Priority	Risk Units	\$ Needed for Project	Allocation?
1	10	\$10,000	Yes
2	6	\$8,000	Yes
3	5	\$5,000	No
4	4	\$4,000	No

Budget=\$19,000

2.3 Interactions and Dependencies in Multi-Hazard Analysis

A scan of the disaster management literature from the affected community perspective highlights four key classes involved in disaster management: The triggering event or disaster(s) and any epiphenomena; the region/community or critical asset(s) affected; intervention strategies implemented; and available resources (such as capital) and accessible community capacities (such as “people skills”) (Faulkner, 2000; McLoughlin, 1985; Mendonça, 2007, Waeckerle, 1991). The four classes listed are irreducible; other elements are present but are collapsible into the four elements highlighted. For example, humanitarian organizations exist but they can be classified in the “available resource or capacity” category, as they provide service to affected communities.

Figure 1 shows relationships among the common classes in the disaster management process, wherein hazards (H) impact the community and its critical assets (C), and management strategies (S) requiring available resources (R) are used to intervene to protect and recover the community/critical assets (C), by mitigating (in some cases) the effect or magnitude of the hazard itself. The point to be noted here with multi-hazard DOM is that the complexity of analysis will often be greatly increased, with both positive and negative effects occurring due to

the multiplicity of hazards, strategies, critical assets, and available resources; these synergies must be considered.

Note that there are two categories of interactions that exist: (i) *Within-Category* dependencies: interactions within the class themselves, e.g., interactions among hazard type 1, hazard type 2, and hazard type 7, say; and (ii) *Among-Category* dependencies: interactions among the different classes, e.g., interactions between the hazard and the community/critical asset.

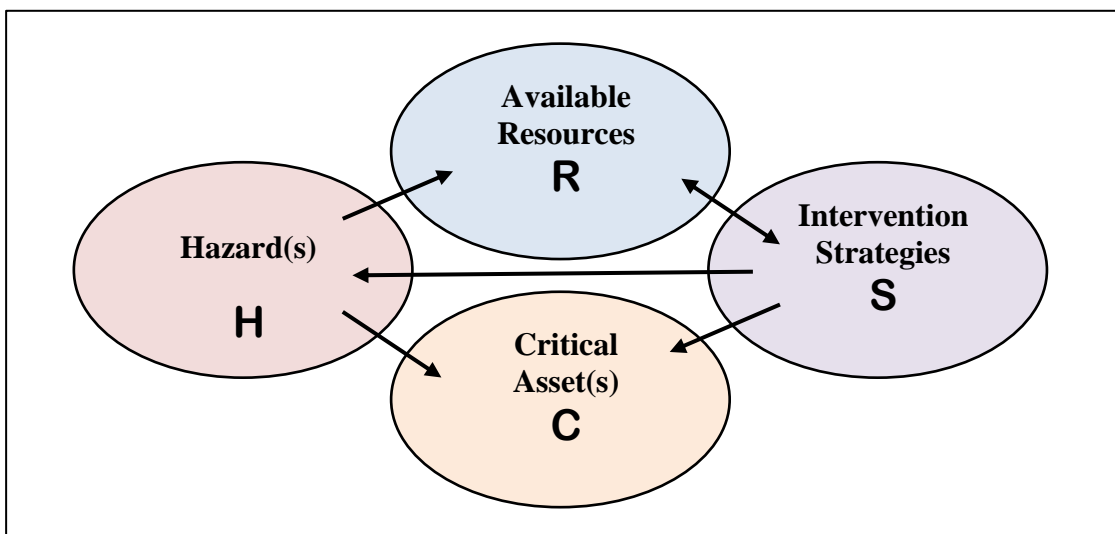


Figure 5-1: Relationships between Disaster Management Elements

Considering only second-order dependencies, there are 4 *within* dependency subsets [H-H; C-C; S-S; and R-R], while there are $\binom{4}{2} = 12$ possible *among* dependencies. [Note that the notation H-H denotes (1) a “hazard to hazard” dependency, which might actually include multiple hazards, such as types 1, 2, and 6, as above; it also means (2) *not* a “hazard to resource” or “hazard to strategy,” etc., dependency.] Of these latter 12, only 6 are typical or practically relevant, as indicated in Figure 1: H=>C; H=>R; S=>H; S=>C; S=>R; and R=>S. Both the single hazard (“mono-hazard”) and multi-hazard literatures mention complex analyses, discussing dependencies and their synergies. In Table 2 we show this literature and organize it

first by *within* and *among* dependencies, and then secondly by the specific type of dependency (e.g., $S \Rightarrow C$). In section 3.5, we show how to model and linearize the dependencies.

2.4 Summary of Analytical Multi-Hazard Models

Typical analytical models in disaster management consider a single type of hazard (Kappes et al., 2012). Moreover, those that consider a range of hazards (analytical multi-hazard models) typically focus on risk reduction (Kappes, et al., 2012), and as a result post disaster management is not considered. This can be seen in Table 3, which provides a summary of the main model features represented in the analytical multi-hazard model literature.

Table 5-2. Model Component Relationships (Within and Among Components)

Component Relationships	Description	Mentioned in Multi-Hazard DM Literature	Mentioned in Mono-Hazard DM Literature
<i>Dependency (Within)</i>			
Hazard – Hazard (H-H)	Interaction between hazards – these present themselves in multiple forms	(Selva et al., 2013; Marzocchi et al., 2012)	x
Critical Asset – Critical Asset (C-C)	Interactions between assets, such as failure dependencies	(Ayyub et al., 2007; Li et al., 2009)	(Maliszewski et al., 2012)
Strategy – Strategy (S-S)	Interactions between strategies, wherein an intervention strategy improves/degrades performance of another strategy	(Chacko, Rees & Zobel, 2014; Stewart & Mueller, 2014)	(Stewart & Mueller, 2013)
Resource – Resource (R-R)	Interactions between resources, such as failure dependencies	x	(McLoughlin, 1985)
<i>Interdependency (Between)</i>			
Strategy – Critical Asset (S-C)	Intervention strategy secures multiple assets	(Dillon et al., 2009)	(McLoughlin, 1985)
Strategy – Available Resources (S-R)	Intervention strategy secures multiple resources	x	(McLoughlin, 1985)
Strategy – Hazard (S-H)	Intervention strategy secures against multiple vulnerabilities	(Caruson & MacManus, 2011; Waugh & Tierney, 2007)	
Hazard – Critical Asset, Resources (H-C / H-R)	Hazard affects multiple assets and resources	(Waugh, 2005; Ayyub et al., 2007)	(McLoughlin, 1985)
Resource – Strategy (R-S)	Application of a resource supports multiple intervention strategies	(Chacko, Rees, & Zobel, 2014)	x

Table 5-3. Features of Analytical Multi-Hazard Models

Disaster Management Phases	Methodologies					Technical features relevant to Multi Hazard							Performance Measures					
	Game Theoretic Approaches	Risk Assessment and Ranking	Cost – Benefit Analysis	Optimization	Other	H-H	C-C	S-S	R-R	S-C	S-R	S-H	H-C / H-R	R-S	Economic Cost	Social Cost Proxy	Time	Other
Primary consideration: Pre-disaster actions																		
Abkowitz & Chatterjee (2012)		✓											✓		✓	*		
Ayyub et al (2007)			✓				✓						✓		✓	✓	✓	✓
Canto-Perello et al (2013)		✓													✓	✓		
Chacko, Rees & Zobel (2014)					✓			✓					✓	✓				✓
Chatterjee & Abkowitz (2011)		✓											✓		✓	*		
Dillon et al (2009)		✓						✓		✓			✓		✓	✓		✓
Hausken et al (2009)	✓											✓			✓			
Li et al (2009)		✓				✓	✓						✓		✓	✓		
Marzochhi et al (2012)		✓			✓	✓									✓	✓		
Selva et al (2013)		✓			✓	✓									✓			
Stewart & Mueller (2014)			✓					✓							✓			
Zhang et al.(2012)					✓													✓
Zhuang & Bier (2007)	✓														✓			
Primary considerations: Post- disaster actions																		
None																		
Primary considerations: Both pre and post disaster actions																		
None																		

* Human casualty and other social costs are converted to a dollar value and represented as an economic cost

As Kappes et al. (2012) indicate, appropriate multi-hazard modeling requires the following key elements: (i) accounting for the additional interactions that exist among disaster management elements; (ii) considering both pre- and post-disaster management concomitantly, which is essential for community/asset viability; and (iii) as noted in Chacko et al. (2014) and Cox (2009), under budget constraints there is a need for mathematical *optimization* models.

As is suggested from Table 3, the only work that provides a complete mathematical optimization model, Zhang et al. (2012), models only resource allocation during disaster response. The model does not account for post-disaster management actions and, moreover, does not account for any interactions. Similarly, Chacko et al. (2014) offer discussion on the objective function and dependency constraints without developing the entire mathematical model, and additionally, do not model post-disaster management. In short, there is no work in the literature that, for multi-hazard analysis, optimizes over the long-term, including both recovery and mitigation, much less accounts for the unique interactions inherent in multi-hazard models.

3.0 Methodology

This section proposes a spatial decision support system (DSS) that emphasizes local community input (together with input from disaster agencies and other governmental units) in order to formulate the decision process. Such a DSS is prescribed for at least three reasons: (1) The decision process is subjective enough that no one methodology can be prescribed for all territories and all hazards; (2) As Berke, Kartez, and Wenger (1993) and Pearce (2003) note, often disaster officials fail to determine and include community members' needs in their planning, resulting in a community that does not want to follow, much less embrace, the planned procedure; and (3) a spatial decision support system is well-suited to the iterative nature of the

problems to be solved jointly by possibly many stakeholders. This section outlines the methodological approach for both the simulation (hazards scenario generator) model and the planning model within the DSS.

3.1 Context-Providing Example

To illustrate the requirements of our DSS, we first describe a scenario in which a community responds to a disaster that has occurred, and in which all emergency response and short-term recovery activities have already concluded. We will develop this scenario into our example of section 4.0, where we utilize the model built in this section (3.0); then we will solve it and show its utility to stakeholders and the community as a new planning framework and tool.

Our example community is Mombasa, Kenya, and in our example we assume there are nine specified disaster operations projects that can be selected there, resources permitting. The implementation of these projects offers a mix of recovery and mitigation over four different geographic regions (Figure 2) against the five disasters (three floods; one tsunami; and one terrorist attack) expected over the 12-year planning-model study period. As a disaster has just occurred and a response is being formulated, we assume information is gathered regarding available resources, current losses, costs, project benefits, project costs, project durations, expected future disaster arrival times, types, and severities for each of the three measures of interest, etc., within the 12 years. All this information is then fed into a parameter database in the DSS, from which it is incorporated as needed by the model base component of the DSS, which contains the mathematical-programming based planning model. Obviously, neither the community nor stakeholders will know which disasters will occur over the next 12 years, how severe each will be, whether economic events unrelated to disasters will affect resources, etc. But at this point in our research, as a first step, we assume that the community makes its planning

decisions based on what it *most expects* the answers to these questions will be. Other choices could be made here such as planning for the worst that could occur, etc., and in future research we address these other valid approaches. But in this paper we take what we believe to be a reasonable first step, given the uncertainty inherent in any such scenario, and decide to formulate the planning model based on the most likely/expected future, given present circumstances.

This model (with this expected-values assumption built in) is then solved in order to determine how to proceed given the current disaster, and the results are stored in the DSS database. Database entries include: (i) decision outcomes, which stipulate which and how much of each of the particular mitigation and recovery projects to undertake, and when to do so for the next 12 years (note these variables could be continuous in general, or could include several binary “go/no-go” decisions); and (ii) measure outcomes, i.e., the values projected, 12 years out, which represent Mombasa’s three assumed community values, namely, the (minimal) human life lost, the (maximal) infrastructure level, and the (optimal level of) jobs lost/regained, as well as a reckoning of resources consumed.

Although the planning model solution described in the previous paragraph contains project start and end dates for the entire 12 years of the planning study period, whenever the next disaster occurs, be it in two months or seven years, a new set of data for the next twelve years is collected, and the entire mathematical programming planning model is rerun. This is done because conditions such as resources available, predicted disaster data, current disaster loss data, etc., may have changed from the last run of the planning model. Based on updated current information, the new run of the model produces output for the same variables as previously, and the new strategy is implemented. When yet another disaster occurs, a new twelve-year horizon is defined, and this process repeats until the 30-year economic study horizon has lapsed.

Note, however, that although these answers *do* state specifically in detail what Mombasa should do *now* in order to meet the community's three objectives as best as possible, these implementation details are *not* the central purpose of the DSS proposed here. Rather, the purpose of the DSS is to provide the community with a sense of what its choice of measures (lives, infrastructure, jobs, etc.) and projects will lead to down the road in the sense of overall community resilience and sustainability. By examining the community's projected responses to 500 different possible scenarios (each thirty-years long, with each disaster generating a new, rolling 12-year study period), as is done with the DSS's simulation component, the community will get a sense as to how it is likely to do (mean, median, range) over the next 30 years on each of its measures. Then the community may re-plan by modifying its set of potential projects; the measures it believes are important and/or their relative ranking or weights; adding new requirements such as equity across regions; etc. The main purpose of the DSS is to serve as a planning tool for the stakeholders.

3.2 Rationale for Methodological Choice

In the previous section it was explained that the approach to be modeled assumes a planning model based on expected events over the next 12 years, given the current disaster and "ambient" community measures, including resources, disaster losses, community measures of importance, etc. The planning model will be re-run upon the manifestation of every new disaster that it obtains.

To represent the future stream of disaster incidents to be faced by the community in the model, we gather historical and predicted data for every type of disaster likely, and failing that, obtain expert opinion. We develop both inter-arrival time and severity distributions for every hazard type, and we generate disasters within a discrete-event simulation program. Each

disaster's occurrence spawns a call to the mathematical programming model in the model base of the DSS, and the expected-value planning model is run over its 12-year study period.

Given the context of the problem highlighted above, the problem is multi-period in nature. In this problem, dynamic programming would be inappropriate because of the presence of continuous decision variables and an infinite number of possible state transitions. Moreover, there is difficulty in getting even experts to specify these particular transition probabilities in a meaningful way. Consequently, we choose mathematical programming with objectives, constraints, and decision variables as the framework within which we build the planning model. The set of objective functions is chosen to be the community's/stakeholders' performance measures, arranged as they see fit, and these objectives are constrained by various resource, policy, geographic, equity, social, etc., constraints. As stated, *expected* values for disaster severities, arrival times, are incorporated in the planning model (although of course the entire probability density function is used for each in the simulation model in producing hazards to be faced by the community).

In summary, disasters (types, frequency, and severity) are generated for a 30-year period, and (as time unfolds) the planning model is run and re-run upon each disaster. At the end of the 30-year period, data are collected. Then a second, 30-year replication is run in the same manner. The process continues until large number (say 500 or 1,000) replications are obtained. Statistics are then generated to summarize the runs. Obviously, the number of replications chosen depends upon the degree of uncertainty in the input data, parameters, etc.

3.3 Notation

Consider a set of possible disaster mitigation projects $\Gamma \{i = 1, \dots, m\}$; a set of regions $R \{r=1, \dots, e\}$; a set of hazards $H \{h=1, \dots, c\}$ likely to impact region R ; and a set of time periods

representing disaster j , $J = \{j=1, \dots, n\}$. To aid in understanding the notation used with *dependency* projects, consider the following example. Assume that a set of projects 1 through 12 is proposed as candidates by the community; then $\Gamma = \{1, 2, \dots, 12\}$. Now suppose that in set Γ there are two project *portfolios* that result in additional benefits. The first portfolio consists of mitigation projects 5 and 6; if both are implemented, an additional benefit of \$300K accrues to the community. To model this, we create a dummy dependency project d_1 , which produces a benefit of \$300K at no cost. (See section 3.5 below for details as to how this dependency is manipulated mathematically to generate the benefit.) The second portfolio consists of mitigation projects 5, 9, and 12; if all three projects are implemented, there is an additional benefit of \$200K. To model this portfolio, we again create a dummy dependency project now called d_2 , which produces a benefit of \$200K at no cost.

Now to complete the notation, define \mathbf{P} to be the set of mitigation project portfolios $\mathbf{P} = \{p_1, p_2, \dots, p_g\}$ consisting of a unique list of project portfolios made up from projects from set Γ . Recall that if the complete portfolio of projects listed in any element of set \mathbf{P} is entirely implemented, then the new additional benefits are assigned to a new dummy dependency project d . The entire set of dependency projects is called $\mathbf{\Delta}$, with $\mathbf{\Delta} = \{d_1, d_2, \dots, d_g\}$. Finally, we define μ_p to be the number of projects that make up portfolio p . Thus in the example given,

$$\Gamma = \{1, 2, \dots, 12\}; \mathbf{P} = \{p_1, p_2\}; \mathbf{\Delta} = \{d_1, d_2\};$$

$p_1 = \{5, 6\}$, which implies $\mu_1=2$, with d_1 generating a benefit of \$300K at no cost; and

$p_2 = \{5, 9, 12\}$, which implies $\mu_2=3$, with d_2 generating a benefit of \$200K at no cost.

3.4 Objectives

A number of disaster operations related studies have been concerned with the terminal value of a measure, by which we mean the value at the end of the decision horizon. For example, Jaller

(2011) employs an objective function that represents benefits that arise based on person-power allocation decisions. The objective function maximizes the total benefits over all periods. While terminal values aid in forming a valid consideration, in situations where a community is under duration of stress, measures that capture the length of time the entity is under stress can be more appropriate. Perez (2011) and Holguin-Veras et al. (2013) appropriately note that in cases where the community is suffering, both the level and duration of suffering needs to be considered – see their excellent discussion on deprivation costs. However, their discussion was limited to relief deprivation. For a community that is under the constant threat of disasters, measures that capture long-term implications such as economic output, infrastructure, quality of life, etc., are also of value. One form of measure used in studies to represent an entity's capacity over time is resilience (Zobel & Khansa, 2012). Consequently, depending on the type of objective considered, terminal value based measures or dynamic measures such as resilience may be appropriate. In the following section, using an example, we develop generalized forms of these appropriate measures.

Example

If a rapid onset disaster with an immediate impact strikes, and if disaster damage is instantaneous, and if recovery is assumed linear, then Figure 4 provides an appropriate example of a system's performance $q(t)$ over a decision horizon $[0, T^*]$.

The choice of a decision horizon T^* can influence the ease with which terminal value and resilience equations can be written. First assume that the expected time of every hazard has been computed. Then if T^* is chosen such that (1) every expected hazard occurs at least once; and (2) T^* does not occur while an expected recovery project is occurring, then the equations for resilience and terminal value will be simplified. Again it should be emphasized that correct

equations may be written even though one or both of the conditions given above do not hold; but these equations will not be as general as those that meet the T^* requirements. In the sequel, we assume that T^* has been defined to meet the above criteria.

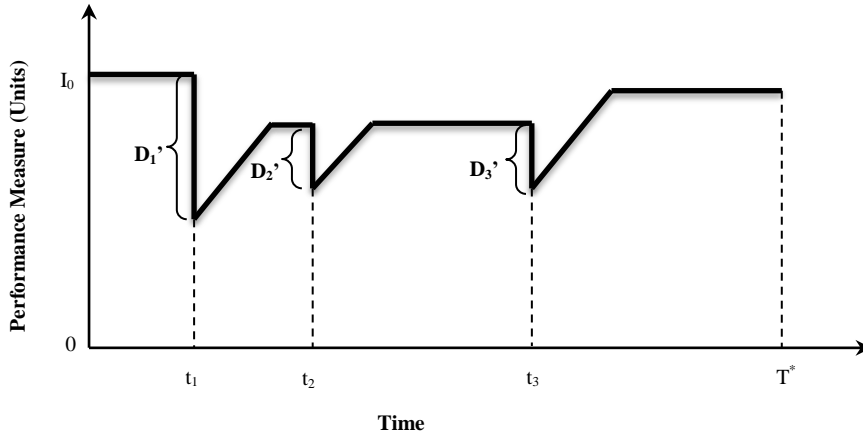


Figure 5-2. Example of System Characteristic over Time

Terminal Value

The terminal-value for the example provided above is $q(T^*)$.

$q(T^*) = \text{Initial Value } (I_o) - \text{Sum of Mitigated disaster damages } (\widetilde{D}_j') + \text{Subsequent Recoveries } (Y_j)$

$$\begin{aligned}
 q(T^*) &= I_o - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \quad ; \quad \widetilde{D}_j' = \widetilde{D}_j - \sum_i (B_i \sum_j X_{i,j-1}) \\
 &= I_o - \sum_j \left(\widetilde{D}_j - \sum_i \left(B_i \sum_j X_{i,j-1} \right) \right) + \sum_j (Y_j) \\
 &= I_o + \sum_j \left(-\widetilde{D}_j + \sum_i \left(B_i \sum_j X_{i,j-1} \right) + Y_j \right), \tag{1}
 \end{aligned}$$

where

i – Index representing mitigation project i ; j – Time period representing disaster j

\widetilde{D}_j – Unmitigated disaster damages at time period j ; \widetilde{D}_j' – Mitigated disaster damages at time period j

B_i – Disaster mitigation benefits of implementing project i .

$X_{i,j} = \begin{cases} 1 - \text{Implementation of project } i \text{ at time period } j \\ 0 - \text{Otherwise} \end{cases}$

Y_j – Amount of recovery planned for time period j

Equation (1) indicates that the terminal value is a function of the initial value minus mitigated disaster damages (mitigation projects implemented before the disaster occurred can have mitigation benefits for the next and subsequent disasters), plus the recovery after each disaster. Equation (1) can be further generalized for a community with several regions (r). In addition, indicator variables (W) can also be included to indicate whether a mitigation project implemented is complete by period j or not. Consequently, equation 1 can be represented by equation (2a):

$$q(T^*) = \sum_r \left(I_{or} + \sum_j \left(-\widetilde{D}_{jr} + \sum_i \left(B_{ir} W_{i,j-1} \sum_j X_{i,j-1} \right) + Y_{jr} \right) \right) \quad (2a)$$

In reality however, disaster severity and Inter-Arrival Times (IATs), being random variables, are sources of uncertainty for this planning model. We deal with this stochastic nature by stipulating that the mathematical model that we build here is an *expected value* planning model. In practice, this is very reasonable. That is, we specify that at any point in time that the community decides to run the resource allocation planning model, it does so based on the known current state of affairs AND also based on its knowledge of what disasters are *expected* to occur, and when they are expected. Hence, we rewrite equation (2a) by replacing the random variable \widetilde{D}_{jr} with its expectation, namely $E[\widetilde{D}_{jr}]$.

$$Q(T^*) = \sum_r \left(I_{or} + \sum_j \left(-E[\widetilde{D}_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) + Y_{jr} \right) \right) \quad (2b)$$

Resilience

In the example of Figure 5-3, the resilience of the system measure $q(t)$ is determined by computing the area under the graph and normalizing it with a term based on a specified decision horizon (T^*) (Zobel, 2010). The area under the graph is

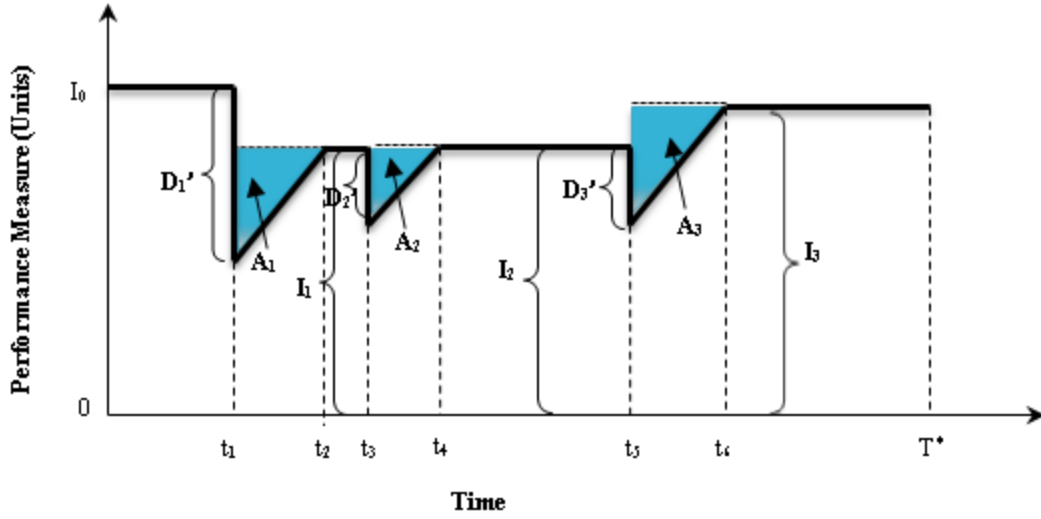


Figure 5-3. Example of System Characteristic over Time: Resilience Case

$$= I_0(t_1) + I_1(t_3 - t_1) + I_2(t_5 - t_3) + I_3(T^* - t_5) - (\sum_{j=1}^3 A_j), \quad (3)$$

where

A_j - Area of triangle j ; B_i – Disaster mitigation benefits of implementing project i ; and

ρ – Rate of recovery coefficient (e.g. \$400K/Year).

Since $I_1 = I_0 - \widetilde{D}_1' + Y_1$; $I_2 = I_1 - \widetilde{D}_2' + Y_2$; $I_3 = I_2 - \widetilde{D}_3' + Y_3$; $A_j = \frac{1}{2} * \rho Y_j * Y_j$,

equation (3) can be rewritten as

$$\text{Area} = I_0(t_1) + (I_0 - \widetilde{D}_1' + Y_1)(t_3 - t_1) + (I_0 - \widetilde{D}_1' + Y_1 - \widetilde{D}_2' + Y_2)(t_5 - t_3) + (I_0 - \widetilde{D}_1' + Y_1 - \widetilde{D}_2' + Y_2 - \widetilde{D}_3' + Y_3)(T^* - t_5) - (\sum_{j=1}^3 \frac{1}{2}(\rho Y_j^2)). \quad (4)$$

In an expected planning model, the disaster IAT random variable can be replaced with its expected value \bar{T} ; thus (4) can be rewritten:

$$= I_0(\bar{T}) + (I_0 - \widetilde{D}_1' + Y_1)(\bar{T}) + (I_0 - \widetilde{D}_1' + Y_1 - \widetilde{D}_2' + Y_2)(\bar{T}) + (I_0 - \widetilde{D}_1' + Y_1 - \widetilde{D}_2' + Y_2 - \widetilde{D}_3' + Y_3)(T^* - t_5) - (\sum_{j=1}^3 \frac{1}{2}(\rho Y_j^2))$$

$$= 3I_0(\bar{T}) + \bar{T}(2(Y_1 - \widetilde{D}_1') + 1(Y_2 - \widetilde{D}_2')) + (I_0 - \widetilde{D}_1' + Y_1 - \widetilde{D}_2' + Y_2 - \widetilde{D}_3' + Y_3)(T^* - t_5) - (\sum_{j=1}^3 \frac{1}{2}(\rho Y_j^2)). \quad (5)$$

Equation 5 can be generalized for any number of disaster periods $j=1, \dots, n$.

$$= (n)\bar{T}I_0 + \bar{T}((n-1)(Y_1 - \widetilde{D}_1') + (n-2)(Y_2 - \widetilde{D}_2') + \dots + 2(Y_{n-2} - \widetilde{D}_{n-2}') + (Y_{n-1} - \widetilde{D}_{n-1}')) + (T^* - t_n) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) - \sum_{j=1}^n \frac{1}{2}(\rho Y_j^2). \quad (6)$$

Because of the manner in which T^* was chosen, $t_n = n \bar{T}$. Therefore, equation (6) can be rewritten as below to give (7):

$$\begin{aligned} &= (n)\bar{T}I_0 + \bar{T}((n-1)(Y_1 - \widetilde{D}_1') + (n-2)(Y_2 - \widetilde{D}_2') + \dots + 2(Y_{n-2} - \widetilde{D}_{n-2}') + (Y_{n-1} - \widetilde{D}_{n-1}')) \\ &\quad + (T^* - n\bar{T}) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) - \sum_{j=1}^n \frac{1}{2}(\rho Y_j^2) \\ &= (n)\bar{T}I_0 + \bar{T}((n-1)(Y_1 - \widetilde{D}_1') + (n-2)(Y_2 - \widetilde{D}_2') + \dots + 2(Y_{n-2} - \widetilde{D}_{n-2}') + (Y_{n-1} - \widetilde{D}_{n-1}')) \\ &\quad - (n\bar{T}) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) + (T^*) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) - \sum_{j=1}^n \frac{1}{2}(\rho Y_j^2) \\ &= \bar{T}((n-1)(Y_1 - \widetilde{D}_1') + (n-2)(Y_2 - \widetilde{D}_2') + \dots + 2(Y_{n-2} - \widetilde{D}_{n-2}') + (Y_{n-1} - \widetilde{D}_{n-1}')) \\ &\quad - (\bar{T})(n(Y_1 - \widetilde{D}_1') + n(Y_2 - \widetilde{D}_2') + \dots + n(Y_{n-2} - \widetilde{D}_{n-2}') + n(Y_{n-1} - \widetilde{D}_{n-1}') + n(Y_n \\ &\quad - \widetilde{D}_n')) + (T^*) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) - \sum_{j=1}^n \frac{1}{2}(\rho Y_j^2) \\ &= (T^*) \left(I_0 - \sum_j (\widetilde{D}_j') + \sum_j (Y_j) \right) - \sum_{j=1}^n \frac{1}{2}(\rho Y_j^2) \\ &\quad - \bar{T} \left((Y_1 - \widetilde{D}_1') + 2(Y_2 - \widetilde{D}_2') + \dots + (n-2)(Y_{n-2} - \widetilde{D}_{n-2}') + (n-1)(Y_{n-1} - \widetilde{D}_{n-1}') + n(Y_n - \widetilde{D}_n') \right) \end{aligned}$$

$$= (T^*) \left(\underbrace{I_o - \sum_j (\widetilde{D}'_j)}_{\text{Terminal Value}} + \sum_j (Y_j) \right) - \bar{T} \left(\sum_j j (Y_j - \widetilde{D}'_j) \right) - \sum_{j=1}^n \frac{1}{2} (\rho Y_j^2) \quad (7)$$

Replacing the random variable \widetilde{D}'_j with its expectation $E[\widetilde{D}_j]$,

$$= (T^*) \left(I_o + \sum_j \left(-E[\widetilde{D}_j] + \sum_i \left(B_i \sum_j X_{i,j-1} \right) + Y_j \right) \right) - \bar{T} \left(\sum_j j \left(Y_j - E[\widetilde{D}_j] + \sum_i \left(B_i \sum_j X_{i,j-1} \right) \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho Y_j^2).$$

This equation can be further generalized for a community with several regions (r). In addition, indicator variables (W) can also be included to indicate whether a mitigation project implemented is complete by period j . This gives

$$= \sum_{r \in R} \left((T^*) \left(I_{or} + \sum_j \left(-E[\widetilde{D}_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) + Y_{jr} \right) \right) - \bar{T} \left(\sum_j j \left(Y_{jr} - E[\widetilde{D}_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho Y_{jr}^2) \right). \quad (8)$$

Note that equation (8) has a non-linear term. However, since (8) is separable, we can reformulate it using linear piecewise approximations of the quadratic term (Williams, 1999).

The quadratic term Y_{jr}^2 is replaced with a linear term K_{jr} , and we add the following three functions to relate the new linear term with the original quadratic term.

$$Y_{jr} - (\beta_1 \lambda_{1jr} + \beta_2 \lambda_{2jr} + \beta_3 \lambda_{3jr} + \dots + \beta_v \lambda_{vjr}) = 0 ; \forall j, r$$

$$K_{jr} - (\beta_1^2 \lambda_{1jr} + \beta_2^2 \lambda_{2jr} + \beta_3^2 \lambda_{3jr} + \dots + \beta_v^2 \lambda_{vjr}) = 0 ; \forall j, r$$

$$\sum_{l=1}^v \lambda_{ljr} = 1 ; \forall j, r ; \lambda_{ljr} \text{ is a SOS2 set.}$$

λ_{ljr} are a special ordered sets of type 2 (SOS2), to ensure the condition that no more than two adjacent λ_{ljr} can be non-zero (Williams, 1999). This condition ensures that the corresponding values of K_{jr} and Y_{jr} lie on one of the straight-line segments.

Equation (8) can now be rewritten to give

$$= \sum_{r \in R} \left((T^*) \left(I_{or} + \sum_j \left(-E[\widetilde{D}_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) + Y_{jr} \right) \right) - \bar{T} \left(\sum_j \left(Y_{jr} - E[\widetilde{D}_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho K_{jr}) \right). \quad (9)$$

In this research we allow a community to specify either terminal-valued measures (2b) or resilience-based measures (9), or any combination of the two forms it chooses.

3.5 Modeling and Linearizing Dependencies

As mentioned, multi-hazard modeling is made more complex by the various dependencies that exist within and among hazards, resources, benefits, costs, and planning. The community itself is modeled in regions, with as many regions of interest allowed as necessary to represent each homogeneous entity of concern. Moreover, these regions include critical assets important to the region. In order to properly model multi-hazard DOM applications, and take advantage of existing synergies, dependencies must be modeled. However modeling dependencies introduces nonlinearities. For example, “IF mitigation project A has already been implemented, AND IF mitigation project B is implemented, THEN combined benefits of the two projects are increased by 30%.” It is well known that such constraints may be linearized using a procedure as exhibited

in Chacko et al. (2014). We illustrate the process for dependencies between projects in regards to benefits; a similar approach is followed for costs, resources, etc.

Consider a matrix of benefits showing the advantage of undertaking simultaneously projects X_i and $X_{i'}$ (example project portfolio):

$$\begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ 0 & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & b_{mm} \end{pmatrix}.$$

where b_{ii} refers to the benefits purely from project i , and $b_{ii'}$ ($i \neq i'$) refers to benefits accruing additionally from the interaction between projects i and i' . If the objective function of the model calculates, for example, the summative benefit of all chosen binary projects, the objective is non-linear due to the non-additive term, as follows:

$$\sum_{i=1}^m \sum_{i'=1}^m b_{ii'} X_i X_{i'}.$$

The objective function can be linearized (see, e.g., Chacko et al., 2014) by (1) adding a new project d , $d \in D$, which is defined as a project that consists of doing projects i and i' *together*, and (2) adding the following logical constraints for each project dependency between any two dependent projects i and i' with $i \neq i'$:

$$2X_d \leq X_i + X_{i'} \leq X_d + 1.$$

These constraints force the new decision variable X_d to be set to a value of one whenever a dependency occurs (i.e., when both projects i and i' are undertaken). The net effect on the overall model is simply the inclusion of the additional constraint above (other than the binary constraint) for each combined project. The benefits matrix becomes a (larger) diagonal matrix, returning the overall model formulation to a linear one.

For a generalized form that applies to two or more dependent projects, the logical constraint is reformulated as follows:

$$\mu_p X_d \leq \sum_i X_i \leq X_d + (\mu_p - 1); \forall d \in \Delta, i \in p \quad (10)$$

where μ_p , represents the number of portfolio projects listed in the unique element p of set P , which can be two, three, etc.

To generalize over several time periods, we reformulate equation (10):

$$\mu_p \sum_j X_{dj} \leq \sum_i \sum_j X_{ij} \leq (\mu_p - 1) + \sum_j X_{dj}; \forall j, d \in \Delta, i \in p \quad (11)$$

The method described above can be similarly applied to cost or resource dependencies, so that these constraints will also be extended in the multi-hazard case. Note that, e.g., as in the benefits case, cost dependencies can be in the form of either savings or additional expenses.

3.6 The Mathematical Programming Resource Allocation Re-Planning Model

Table 5-4: Planning Model Notation

X_{ij}	Select mitigation project i at time period j	$X_{ij} \in \{0,1\}$
Y_{jr}	Amount of recovery at time period j for region r	$Y_{jr} \geq 0$; Units: Dollars
Q	Maximum percent deviation from target	-
I_{0r}	Initial value of economic output of region r	Dollars
B_{ir}	Economic benefits arising from implementing mitigation project i , in region r	Dollars
B'_{ir}	Benefits arising from implementing mitigation project i , protecting community members in region r	Lives
C_{ij}	Cost of implementing mitigation project i , at time period j	Dollars
$E[\widetilde{D}_{jr}]$	Expected disaster damages on economic output at time period j , region r	Dollars
$E[\widetilde{D}'_{jr}]$	Expected loss of lives at time period j , region r	Lives
$E[\widetilde{T}]$	Expected disaster IAT	Time: Years
ρ	Rate of recovery coefficient	Economic recovery per year. e.g. \$400K/year
$M_{h,j}$	Budget earmarked for hazard h , at period j	Dollars
$M_{c,j}$	Common budget pool, no associated earmarks, at period j	Dollars
M_{j-1}^U	Unused budget resourced in period $j-1$	Dollars
λ_{vjr}	Weights attributed to each linear approximation component v	$\lambda_{vjr} \in [0,1]$

K_{jr}	Linear term replacing quadratic Y_{jr}^2 term	-
$W_{i,j}$	Mitigation project i complete by period j	$W_{i,j} \in \{0,1\}$
T^*	Decision horizon	Years
β_v	Discrete steps representing values of Y_{jr} for each linear component	Units similar to recovery term linearized
Z_{Output}^{Max}	Objective Measure's Target value (Maximum value for Economic Output)	Dollars
Z_{Lives}^{Max}	Objective Measure's Target value (Maximum value for Lives)	Lives
Z_{Output}	Objective Measure	Dollars
Z_{Lives}	Objective Measure	Lives
μ_p	Number of projects that make up project portfolio p	Units
S_o	Subjective weight for Economic Output measure	-
S_l	Subjective weight for Lives measure	-

3.6.1 Decision Variables. Decisions under the system's consideration include the choice of disaster mitigation projects to be implemented as well as the desired time of each project's execution, and the set of recovery decisions, namely the desired recovery level and when said recovery is implemented.

$X_{ij} = 1$ if mitigation project i is selected at time period j ; $X_{ij} \in \{0,1\}$

Y_{jr} – Amount of recovery of system capacity over time period j for region r ; $Y_{jr} \geq 0$

Consequently, we have a mixed integer programming problem.

3.6.2 Objectives. In general, the objective may be the minimization or maximization of a single objective; it may be multi-objective; etc. As mentioned, there are two general forms of each objective that we consider: the resilience form (9) and a terminal form (2b). In the former, the concern is to “bounce back” as quickly and as much as possible to (or above) the initial value; in the latter, the concern is to achieve as large a value as possible at the conclusion of the economic horizon, regardless of the speed in which this is done.

$$Z = \sum_r \left(I_{or} + \sum_j \left(-E[D_{jr}] + \sum_i \left(B_{ir} W_{i,j-1} \sum_j X_{i,j-1} \right) + Y_{jr} \right) \right); \text{ Terminal form}$$

$$Z = \sum_{r \in R} \left((n+1) \bar{T} I_{or} + \bar{T} \sum_{m=1}^n \sum_{j=1}^m \left(Y_{jr} - E[D_{jr}] + \sum_i \left(B_{ir} W_{i,j-1} \sum_j X_{i,j-1} \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho K_{jr}) \right); \text{ Resilience Form}$$

3.6.3 Example. Assume two measures are utilized: (1) maximize the terminal value of lives not lost as a result of disasters (assuming non-disaster birth and death rates are equal over the decision horizon); and (2) maximize the resilience of what we term ‘economic output’ (this may include infrastructure). Then combining the two objectives into one objective using a MINIMAX MOLP approach (Ragsdale, 2014), the following formulation results.

Minimize: Q

Subject to:

$$S_O \left(\frac{Z_{Output}^{Max} - Z_{Output}}{Z_{Output}^{Max}} \right) \leq Q$$

$$S_L \left(\frac{Z_{Lives}^{Max} - Z_{Lives}}{Z_{Lives}^{Max}} \right) \leq Q$$

$$Z_{Lives} = \sum_r \left(I'_{or} + \sum_j \left(-E[D'_{jr}] + \sum_i \left(B'_{ir} W_{i,j-1} \sum_j X_{i,j-1} \right) \right) \right)$$

$$Z_{Output} = \sum_{r \in R} \left((n+1) \bar{T} I_{or} + \bar{T} \sum_{m=1}^n \sum_{j=1}^m \left(Y_{jr} - E[D_{jr}] + \sum_i \left(B_{ir} W_{i,j-1} \sum_j X_{i,j-1} \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho K_{jr}) \right)$$

Piecewise Linearization Constraints

$$Y_{jr} - (\beta_1 \lambda_{1jr} + \beta_2 \lambda_{2jr} + \beta_3 \lambda_{3jr} + \dots + \beta_v \lambda_{vjr}) = 0 ; \forall j, r$$

$$K_{jr} - (\beta_1^2 \lambda_{1jr} + \beta_2^2 \lambda_{2jr} + \beta_3^2 \lambda_{3jr} + \dots + \beta_v^2 \lambda_{vjr}) = 0 ; \forall j, r$$

$$\sum_{l=1}^v \lambda_{ljr} = 1 ; \forall j, r ; \lambda_{ljr} \text{ is a SOS2 set}$$

Resource Constraints

$$\sum_{i \in I^h} C_{ij} X_{ij} \leq M_{hj}; \quad \forall j \in J, \forall h \in H$$

$$\sum_{r \in R} Y_{jr} \leq M_{c,j} + M_{j-1}^U; \quad \forall j \in J$$

$$\sum_{i \in I} C_{ij} X_{ij} + \sum_{r \in R} Y_{jr} \leq \sum_{h \in H} (M_{h,j}) + M_{c,j} + M_{j-1}^U; \quad \forall j \in J$$

$$\sum_{h \in H} (M_{h,j}) + M_{c,j} + M_{j-1}^U = \sum_i C_{ij} X_{ij} + \sum_r Y_{jr} + M_j^U; \quad \forall j \in J$$

Linearization Constraints (For Dependency Projects)

$$\mu \sum_j X_{dj} \leq \sum_i \sum_j X_{ij} \leq (\mu - 1) + \sum_j X_{dj}; \quad \forall j; \text{ where } d \in D, i \in p$$

Operational Constraints

$$\sum_j X_{ij} \leq 1; \quad \forall i \in I$$

Non-Negativity Constraints

$$X_{ij} \geq 0; \quad \forall i \in I, j \in J$$

$$Y_{jr} \geq 0; \quad \forall j \in J, r \in R$$

$$K_{jr} \geq 0; \quad j \in J, r \in R$$

$$\lambda_{vjr} \geq 0; \quad \forall v, j \in J, r \in R.$$

4.0 Example

The example discussed here is a case study of Mombasa, Kenya. In this research we focus on three key hazards, listed in the literature, that have historically impacted, and are expected to be of significant future impact, namely *flooding*, *terrorism*, and *tsunamis*.

Hazards

Flooding

Projections indicate that 17 per cent of Mombasa would be submerged with a sea-level rise of only 30 centimeters, leading to displacement of people due to flooding, water-logged soils, and

reduced crop production caused by salt stress (Awuor et al., 2008). A study by the Tyndall Centre, based on the A1B sea-level and socioeconomic scenario, suggests that a 1-in-100-year extreme water event (e.g., storm surge) would affect 190,000 people and US\$470 million in assets, and that this exposure would increase to over 380,000 people and US\$15 billion in assets by 2080 due to socioeconomic and, to a lesser extent, climatic factors (Kebede et al., 2010). About 60% of this exposure is concentrated on Mombasa Island (see below and Figure 2).

Terrorism

Al-Shabaab is a Somali group that was designated as a foreign terrorist organization by the U.S. government in 2008. Its purpose is to turn Somalia into a fundamentalist Islamic state. The group is believed to be responsible for attacks in Somalia that have killed international aid workers, journalists, civilian leaders and African Union peacekeepers, and it claimed responsibility for the July 2010 suicide bombings in Kampala, Uganda, that killed more than 70 people, including a U.S. citizen, as they gathered to watch a World Cup final soccer match.

In February 2012, the group's leader, Ahmed Abdi aw-Mohamed, and al Qaeda leader Ayman al-Zawahiri released a video announcing the alliance of the two organizations. "I would say that the greatest risks right now in East Africa are Al-Shabaab and the violent extremists that they represent," said Gen. Carter Ham in 2011, when he was commander of the U.S. Africa Command (Watkins (CNN), 2014).

Tsunami

Several studies (Amollo, 2007; Ngunjiri, 2007; Mulwa, Kimata & Nguyen, 2013; Owour et al., 2008) particularly those from the staff members of the Kenya Metrological Society, highlight tsunamis as a major concern for the Kenyan coast. These reports highlight the impacts from both the near-field tsunami risk source from the Davie ridge and far-field risks (like the tsunami that

occurred off Indonesia in 2001). (However, Parry et al., (2012) disagree with the contention that Tsunami's are a significant risk source to the Kenyan coast line).

Community Measures/Values

The three measures chosen for Mombasa are (1) the terminal value of human life; (2) infrastructure/economic output resilience; and (3) the resilience of the job market (number of jobs sustained in the region).

Regions

Mombasa district is split into four main regions, Mombasa Island, Likoni, Changamwe, and Kisauni (Awour et al., 2008). We adopt these as four regions in our study. See Figure 5-4.



Figure 5-4: Mombasa, Kenya (Google Earth, 2014. Map Data: DigitalGlobe, CNES/Astrium)

Projects and Dependencies

The three hazards listed earlier are not known to have significant secondary interactions (e.g., flooding does not generally cause terrorism); consequently such interactions are not modeled in the simulation model. However, the simulation model does allow for the simultaneous occurrence of these hazards, as part of the hazard-hazard dependency that we are incorporating.

We consider six possible mitigation projects and one recovery type of project that represents a variable degree of recovery prescribed for by the planning model. These projects vary in purpose and include the possibility of building a seawall near the island inlet to protect against tsunamis and floods; maintaining the ecological habitat by protecting mangrove areas near the coast against flooding; installing CCTV, particularly near the airport, refinery, and the power generation system (the Appendix contains a full listing of projects). Resources are not sufficient to undertake all projects. Moreover, it is possible that this set of projects may not provide adequate protection against all hazards. One advantage of the proposed DSS is to evaluate the coverage provided by them and to help highlight areas of inadequacy.

Dependencies between projects are illustrated in this paper by including two different dependencies. If projects 1 and 2 are done concurrently, or project 2 is started after 1 is completed, then mitigation benefits occur. Moreover, if projects 5 and 6 are both undertaken – in *any* order – then when both are completed, resource savings are obtained. Thus, there are seven ‘real’ projects plus two ‘dependency’ projects for a total of nine.

Mathematical Model

See the Appendix for the mathematical model for Mombasa, Kenya, in which a MINIMAX mixed integer MOLP model is implemented. Section 4.1 provides an overview of the measures tracked over a defined 30-year economic study horizon.

4.1 Results

Figure 5-5a shows a plot of the first community value (CV) measure, the terminal value of human lives *not lost*, when simulated 500 times over the economic study horizon (30 years). The median value obtained is shown in red; the mean value in blue; and the 10th and 90th percentiles of values at each point in time are shown by the extent of the vertical lines. Note that the model does not include the dynamic flow of people in and out of the community under evaluation; this is to ensure that the results are based on an initial value from which comparisons can be made directly at the end of the decision horizon. Further note that human lives can only be protected and are not recoverable.

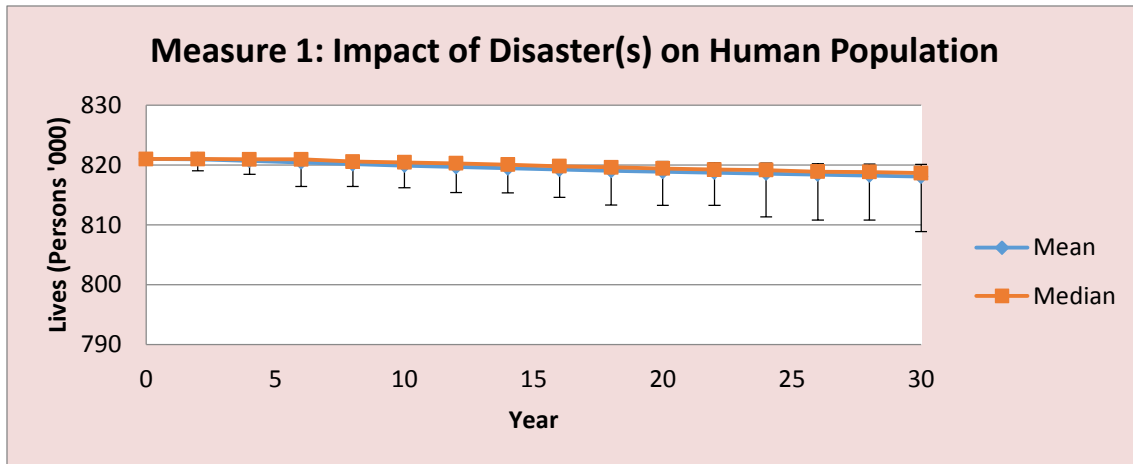


Figure 5-5a

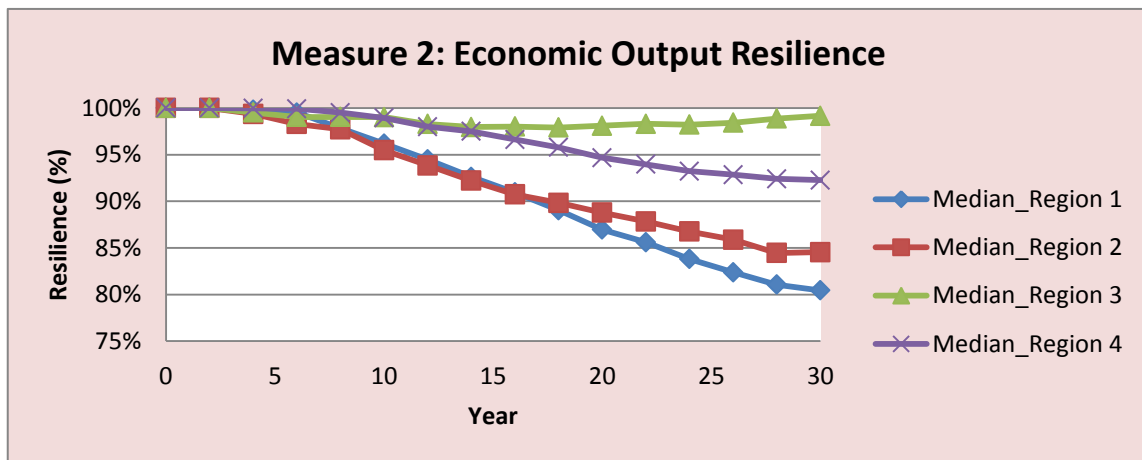


Figure 5-5b

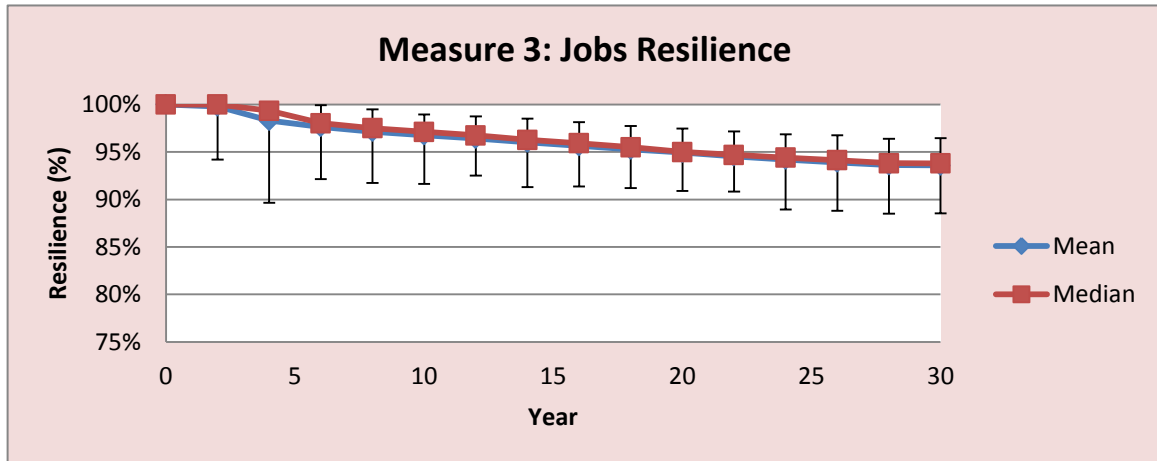


Figure 5-5c

Figure 5-5. Multi-Hazard Analysis (Three Measures Chosen) for Mombasa, Kenya

Figure 5-5b is a graph representing economic output resilience of Mombasa over the 30-year time frame. Note that the individual behaviors of each of the four regions. Observe that once the mitigation projects are completed, disaster impacts are lessened and resources begin shifting towards recovery, as can be noted close to the end of the decision horizon with the resilience curve starting to flatten. Figure 5-5c demonstrates the Mombasa job profile for the study period. These three figures show the exposure the community faces with the given resources at its disposal and the “nine” projects it has decided to consider, based upon our expected-value planning model that includes both mitigation and recovery considerations. The community may decide that it needs to propose additional projects (e.g., per Figure 5-5b, is the infrastructure in region 1 sufficiently protected?), procure additional funding, or change its measures of import in order to better shield itself from the range of possibilities likely in its future.

Examining outputs under different scenarios *does* lead to instruction to the community and other stakeholders in better understanding effects from potential decisions. Selecting and investigating additional social measures of import, as well as adjusting the relative importance of chosen objectives is a study that is better preformed before disasters strike than after.

5.0 DISCUSSION

Whether Mombasa is analyzed with a single community objective, or whether stakeholders include all relevant hazards or not, will of course have no effect upon what disasters actually occur for the next thirty years. But what the following brief sections demonstrate is that it certainly does matter whether the community fails to plan with adequate objectives or consideration of hazards that actually will occur. This point is obvious, but is meant to emphasize the need to step beyond current approaches in the literature.

5.1 Failure to Analyze Mombasa as Multi-Hazard

Failure to conduct multi-hazard analyses, and instead focusing on a single hazard (even if it's the most common hazard) can lead to both a failure to be cognizant of epiphenomena and cascading effects, as well as an inability to capitalize on synergistic efficiencies, such as the synchronic selection of projects. Planning for only the single, most common hazard may in fact do better in the short-term (Figure 5-6b), but in the long-term, losses can be significantly more dramatic (Figure 5-6a & 5-6b). Note in both these figures the *spread* of the simulation runs – not just the means, may be impacted. In Mombasa under the conditions analyzed, regions will suffer far more in most cases and particularly in worst-case scenarios both with respect to lives lost and economic output foregone.

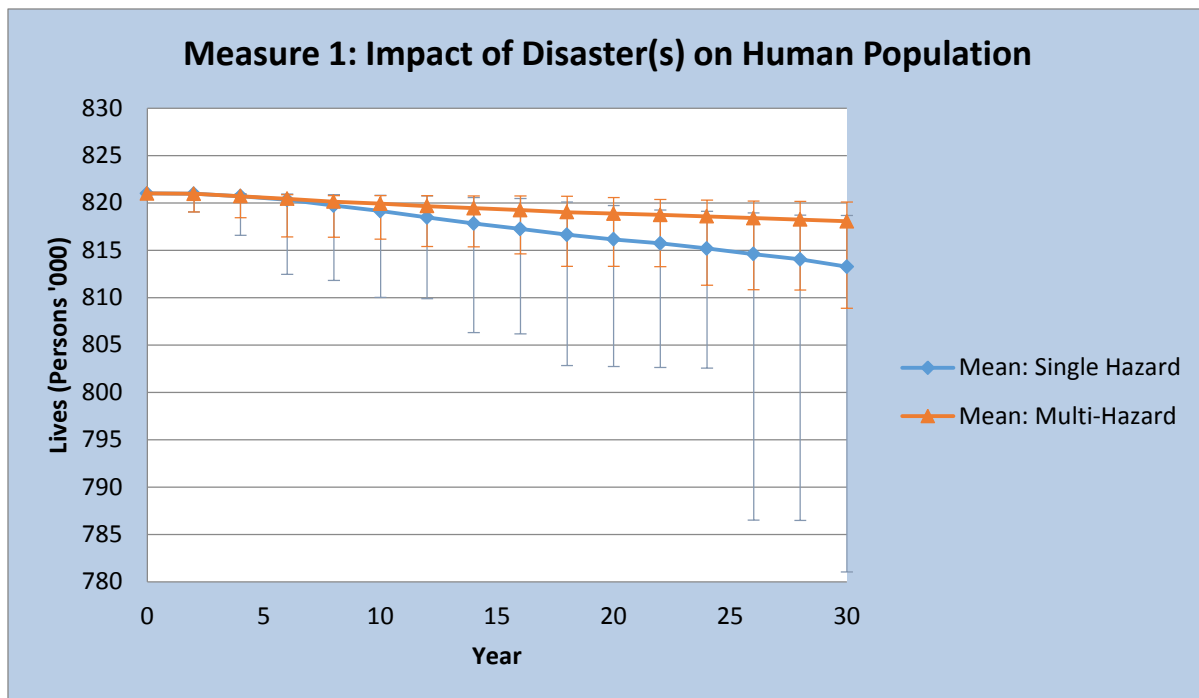


Figure 5-6a

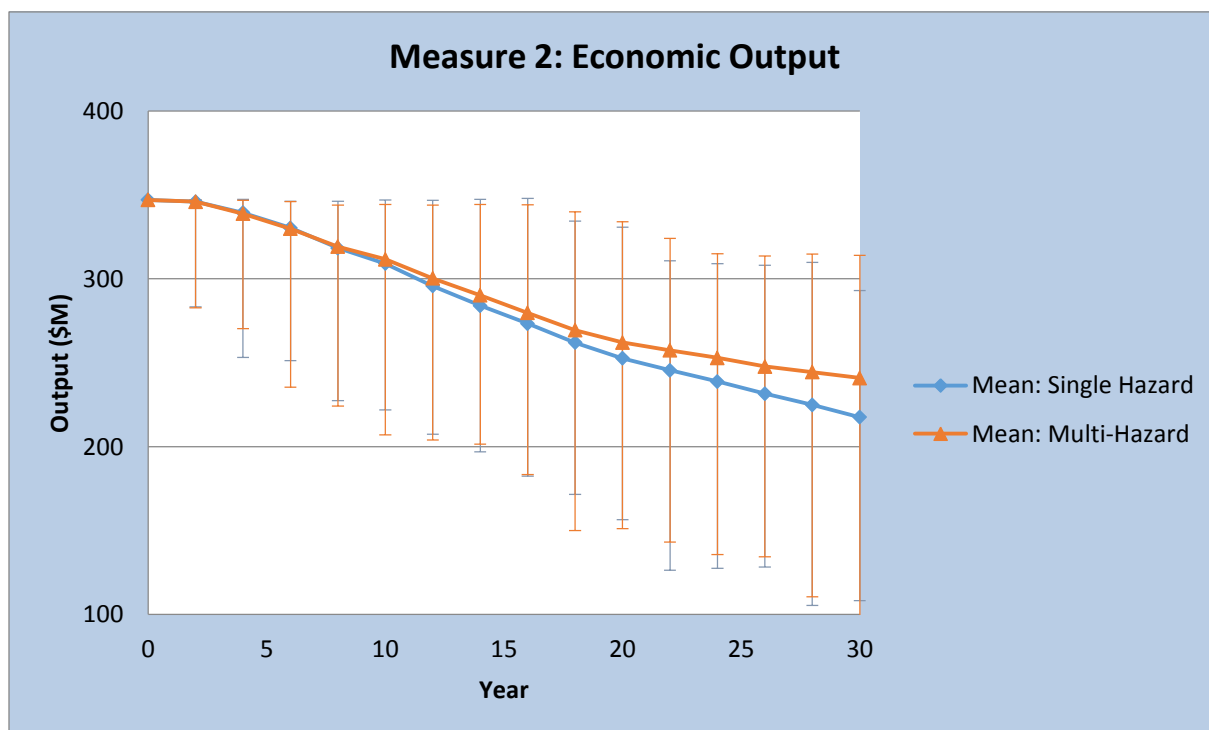


Figure 5-6b

Figure 5-6. Planning for Only the Single Most Prevalent Hazard in Mombasa, Kenya

5.2 Analyzing Mombasa with a Single Objective

The consideration of a single objective offers an interesting angle to this discussion. In this case, we compare the multi-objective model against a purely economic model both under multi-hazard conditions. As expected, the single objective model outperforms under the economic measure but does poorly under lives and jobs. If the community truly cares about lives as its highest priority, this outcome will be unacceptable – or at least may contribute to a highly unfortunate, unnecessary loss of human life.

6.0 CONCLUSIONS

This research presents a Decision Support System utilizing a model that considers the necessity of long-range disaster planning with both mitigation and recovery considerations included within a multi-hazard framework. The model consists of an embedded, expected-value, multi-objective mathematical programming formulation that is utilized for planning upon occurrence of every disaster. An example taken from East Africa was furnished. The DSS can be used in an iterative fashion to examine the effect of project inclusions as well as changes in measures/community values.

The major way in which the authors believe this first-step in proper long-term planning should be extended is the inclusion of various kinds of uncertainty in the present expected-value planning model. In particular, the ability to investigate and plan against black swan events as well as using, for example, conditional-variance-at risk analyses with (say) fuzzy sets should be added to the DSS. The authors are in the process of developing such additions.

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APPENDIX

Objectives:

Maximize: Z_{Output}

Maximize: Z_{Jobs}

Maximize: Z_{Lives}

$$Z_{Lives} = \sum_r \left(I'_{or} + \sum_j \left(-E[D'_{jr}] + \sum_i \left(B'_{ir} W_{i,j} \sum_j X_{i,j-1} \right) \right) \right)$$

$$Z_{Output} = \sum_{r \in R} \left((n+1)\bar{T}I_{or} + \bar{T} \sum_{m=1}^n \sum_{j=1}^m \left(Y_{jr} - E[D_{jr}] + \sum_i \left(B_{ir} W_{i,j} \sum_j X_{i,j-1} \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho K_{jr}) \right)$$

$$Z_{Jobs} = \sum_{r \in R} \left((n+1)\bar{T}I''_{or} + \bar{T} \sum_{m=1}^n \sum_{j=1}^m \left(Y''_{jr} - E[D''_{jr}] + \sum_i \left(B''_{ir} W_{i,j} \sum_j X_{i,j-1} \right) \right) - \sum_{j=1}^n \frac{1}{2} (\rho K''_{jr}) \right)$$

Subject to:

$$K_{jr} = Y_{jr}^2$$

$$Y_{jr} - (\delta_1 \lambda_{1jr} + \delta_2 \lambda_{2jr} + \delta_3 \lambda_{3jr} + \dots + \delta_v \lambda_{vjr}) = 0 ; \forall j \in J, r \in R$$

$$K_{jr} - (\delta_1^2 \lambda_{1jr} + \delta_2^2 \lambda_{2jr} + \delta_3^2 \lambda_{3jr} + \dots + \delta_v^2 \lambda_{vjr}) = 0 ; \forall j \in J, r \in R$$

$$\sum_{l=1}^v \lambda_{ljr} = 1 ; \forall j, r ; \lambda_{ljr} \text{ is a SOS2 set}$$

$$Y_{jr} \leq \bar{T}/\rho$$

$$K''_{jr} = (Y'_{jr})^2$$

$$Y'_{jr} - (\delta'_1 \lambda'_{1jr} + \delta'_2 \lambda'_{2jr} + \delta'_3 \lambda'_{3jr} + \dots + \delta'_v \lambda'_{vjr}) = 0 ; \forall j \in J, r \in R$$

$$K''_{jr} - (\delta_1'^2 \lambda_{1jr} + \delta_2'^2 \lambda_{2jr} + \delta_3'^2 \lambda_{3jr} + \dots + \delta_v'^2 \lambda_{vjr}) = 0 ; \forall j \in J, r \in R$$

$$\sum_{l=1}^v \lambda'_{ljr} = 1 ; \forall j, r ; \lambda'_{ljr} \text{ is a SOS2 set}$$

$$Y'_{jr} \leq \bar{T}/\rho'$$

Resource Constraint

$$\sum_{i \in F} C_{ij} X_{ij} \leq M_{fj} ; \forall j \in J$$

$$\sum_{i \in T} C_{ij} X_{ij} \leq M_{tj} ; \forall j \in J$$

$$\sum_{i \in TA} C_{ij} X_{ij} \leq M_{ta,j} ; \forall j \in J$$

$$\sum_{r \in R} Y_{jr} \leq M_{c,j} + M_{j-1}^U ; \forall j \in J$$

$$\sum_{i \in I} C_{ij} X_{ij} + \sum_{r \in R} (Y_{jr} + Y'_{jr}) \leq M_{f,j} + M_{t,j} + M_{ta,j} + M_{c,j} + M_{j-1}^U ; \forall j \in J$$

$$\sum_{h \in H} (M_{h,j}) + M_{c,j} + M_{j-1}^U = \sum_i C_{ij} X_{ij} + \sum_r Y_{jr} + M_j^U; \forall j \in J$$

Linearization Constraints (For Dependency Projects)

$$2 \sum_j X_{ij} \leq \sum_{i \in P} \sum_j X_{ij} \leq 1 + \sum_j X_{ij}; \forall j \in J$$

Policy Constraints

Set decision variables of some projects to zero and or adjust resource allocation to certain regions.

Operational Constraints

$$\sum_j X_{ij} \leq 1; \forall i \in I$$

Non-Negativity Constraints

$$X_{ij} \geq 0; \forall i \in I, j \in J$$

$$Y_{jr} \geq 0; \forall j \in J, r \in R$$

$$Y'_{jr} \geq 0; j \in J, r \in R$$

$$K_{jr} \geq 0; j \in J, r \in R$$

$$K'_{jr} \geq 0; j \in J, r \in R$$

$$\lambda_{vjr} \geq 0; \forall v, j \in J, r \in R$$

Combining the three objectives into one objective using a Min-Max MOLP approach results in the following adjustments:

Targets are obtained by solving for each objective separately and determining the maximum possible measure value. Targets are resolved for after a disaster strikes, on a rolling 12 year horizon.

$$Z_{OT}^{Max} - \text{Output target}$$

$$Z_{JS}^{Max} - \text{Jobs target}$$

$$Z_{LE}^{Max} - \text{Lives target}$$

Minimize: Q

Subject to:

$$W_O \left(\frac{Z_{OT}^{Max} - Z_{OT}}{Z_{OT}^{Max}} \right) \leq Q$$

$$W_J \left(\frac{Z_{JS}^{Max} - Z_{JS}}{Z_{JS}^{Max}} \right) \leq Q$$

$$W_L \left(\frac{Z_{LE}^{Max} - Z_{LE}}{Z_{LE}^{Max}} \right) \leq Q$$

Table A.1. Project Description

1	Project A – Phase I	Development of an integrated surveillance system over Mombasa Island and Changamwe. This system will provide emergency personnel vital information to deter future attacks, and provide important information in case of disaster response and recovery.
2	Project A – Phase II	Phase II of project A is an intensive campaign to have the public to be careful and keep an eye for unattended objects, suspicious people or activities.
3	Project B	Land Management policies to protect and advance mangrove forests on the Kenyan shore, protection of natural beaches, limiting human settlement in natural flood plains.
4	Project C	Early warning system to warn about Tsunami's and floods.
5	Project D	Building sea walls at the inlet near Mombasa island (4)
6	Project E	Projects focused on upgrading the flood resilience of Mombasa (all regions, mostly in 2 and 3) through vulnerability mapping, training etc.
7	Project F	Benefits dependency between Project A-I and A-II. Implementing A-I and A-II together results in more benefits than A & B separately
8	Project G	Resource dependency. Implementing both project D and E will result in volume discounts

CHAPTER 6: SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

Summary

This dissertation emphasizes the importance of sustainability in disaster operations management, shifting the focus from disaster relief to community viability and stability in the long-term. Using the sustainability literature in disaster operations, this dissertation proposes a framework for sustainability-driven disaster planning. The implications of this framework provide two natural extensions for analytic models in disaster operations.

The first extension, addressed in Chapter 4, emphasizes the importance of planning for the tradeoff between mitigation and long-term recovery, under a long-term decision horizon in which multiple disasters can occur. The shift of temporal focus from a single-disaster epoch to a long-term decision horizon is critical to a community's long-term viability, particularly given the environmental context: the cyclical and recurrent nature of natural hazards and the projected increase in the frequency of weather extremes over the coming decades.

The second extension, addressed in Chapter 5, enables planning in the face of multiple sources of hazards. Planning for one type of hazard can be detrimental to a community, particularly if it faces risks from more than one hazard source, a point clearly highlighted in the analysis conducted in Chapter 5.

Conclusions

The first study (Chapter 3) offers a discussion on disaster operations management and the importance of focusing on the outcomes related to community viability. The study highlights the need for managing disasters as continuous operations rather than transient operations (like a project such as humanitarian relief). This need is particularly crucial for communities that face a recurrent cycle of disasters, such as the natural hazards many communities experience. This

study demonstrates the importance of sustainable disaster planning and consequently provides a framework in which such planning can occur, thus supporting the long-term viability of the affected community. This framework offered in Chapter 3 proved successful, in that the quantitative models developed in both Chapters 4 and 5 had the structure to support the goal of providing sustainable planning tools, first in the single-hazard and then in the multi-hazard, environment.

The quantitative analyses offered in the second and third study were aimed at highlighting the possible tradeoffs and benefits of considering a sustainability-based DOM planning model. The most significant results of these analyses however were not targeted at prescribing the best sequence of activities given the various disaster scenarios a community might encounter; rather the analyses provided long-term plots versus time of measures of concern to the community. With this type of feedback, communities will now be able to study the sustainability impact of their decisions before having to commit to a plan.

The second study provided an optimization-based planning model that integrated mitigation and long-term recovery for multi-event cases of a single hazard type that occur over a long decision horizon. The results of the analysis underscored the importance of considering a community's 'duration under stress' in the objective function. Moreover, the simulation model demonstrated how some decision policies outperformed others, thereby providing vital information for further discussions on tradeoffs.

The final study derived a multi-objective optimization planning model that also integrated mitigation and long-term recovery, but now for the multi-event and multi-hazard case. Besides furnishing a valuable planning tool, the results of the analysis reinforce the danger of

employing mono-hazard models instead of multi-hazard models. The study also clearly showed the effects of modeling with a single objective as opposed to a set of objectives.

Future Work

The work carried out in this dissertation made several assumptions in order to develop an initial set of sustainability-based models in disaster operations planning. This dissertation has driven the possibility and value of sustainability-based models home, using a variety of qualitative and analytic studies. Now that the importance and feasibility of such models has been proven, the next step of making them even more realistic can be pursued. In particular, this research can be extended in the following ways:

- (i). When modeling uncertainty, disaster planners need to properly recommend how to deal with so-called black swan events – events that are highly unlikely, but if they occur, turn out to be devastating. As is evident in the results shown in Chapter 4, black swan type events can have a significant impact on the long-term sustainability of the community, resulting in decades before a community manages to recover to some sense of normalcy. Part of the process in addressing this kind of event is determining appropriate performance measures. Disaster management decisions (or the selection of decision policies) that are based on expected values or basic risk measures (e.g., VAR) are inadequate. Models using measures such as conditional variance at risk (CVAR) may be more appropriate when considering such extremes.
- (ii). A long-term decision horizon results in a more uncertain decision making environment, this is evident when looking at the spread for the results offered in Chapters 4 and 5; as can be seen from the figures in those chapters, this problem is intensified in the multi-hazard case. Superior decision models, would consider the variance spread in the objectives, as it is preferable to have robust decision policies than those sensitive to disaster fluctuations.

(iii). The dissertation assumed that model parameters are deterministic, whereas in reality, many (or even most) of the cost/resource etc. parameters involved are stochastic in nature. There is an important extension that can be made here, particularly if the decision models offered are sensitive to disaster and model parameters. For example, in reality many disaster resources are dynamic both temporally and spatially. Availability of resources in itself is a significant area of research in the disaster management field, as noted in Starr and Van Wassenhove (2014). Future research in modeling the non-static behavior of resources may use as an example the work of Salmeron & Apte (2009); this particular work models asset prepositioning while accounting for the dynamic nature of resources over time.

(iv). Finally, as emphasized in the literature review of this dissertation, decision policy performance is dependent on the disaster nature. A location that has fewer disasters will result in better performance for pure-recovery based policies than pure-mitigation based ones (see Figure 6-1). There is need to conduct this type of tradeoff analysis to offer insight into decision policy selection. The planning models developed and proposed in this dissertation can be used to garner this insight.

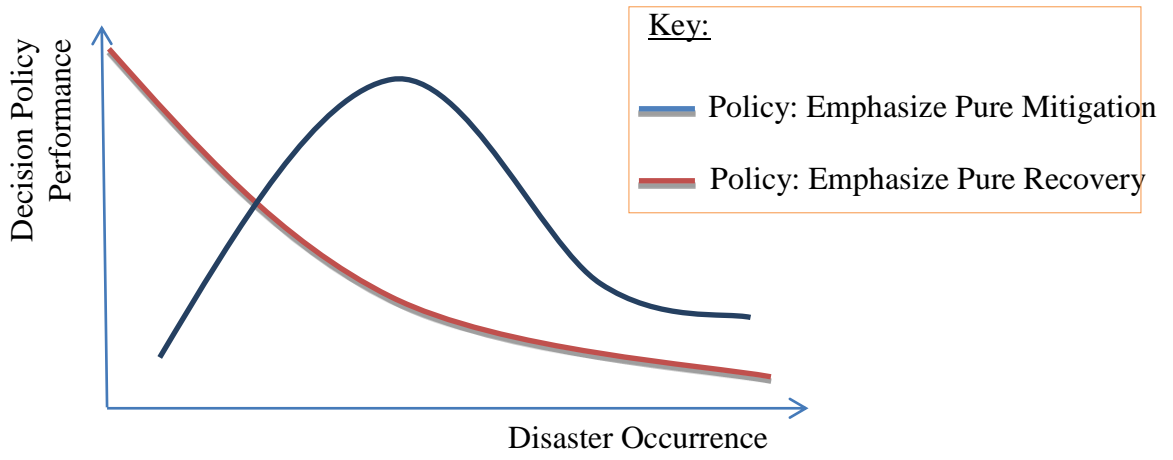


Figure 6-1: Decision Policy Performance Characterization

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