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A Multi-Objective Decision-Making Model for Resources Allocation in Humanitarian Relief

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THESIS

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Abstract

This thesis addresses the critical resource allocation in the initial days of a disaster relief operation. One of the most important and essential components of relief operations is the allocation of scarce resources to accomplish the relief efforts. Every operation for disaster relief needs various critical resources including (but not limited to) personnel, equipment, supplies, or simply finances. Several research efforts for disaster relief have suggested methods to allocate scarce resources across a variety of competing objectives and programs in a disaster relief operation. Many of those efforts focused on optimizing a mathematical programming model subject to budget constraints. However, capturing the values of the decision-maker(s) in such a model is relatively unexplored. The lack of clear organizational values contributes to the inconsistency in practice and hinders effective resource allocation across the disaster relief system.

The purpose of this study is to develop a multi-objective decision-making (MODM) model to incorporate the decision-maker(s) value trade-offs in the disaster relief resources allocation problem. The notional model is based on a hurricane and flood scenario, and the decision window for the resource allocation is the critical first 72 hours after the initial damage assessment has been made. The value focused thinking (VFT) process is used to capture the value trade-offs, and the resulting value hierarchy is optimized via a mathematical programming model to solve the multi-objective resource allocation problem.

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Dedication

To my ROK Army and lovely wife

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Seungbae Park

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1. Introduction

1.1 Background

> "In general, we think of disasters occurring in far-off lands whose populations are hidden by the anonymity of distance. This may be true of many of the more recent notable disasters, such as the Asian tsunami of 2005 that killed over 250,000 people and the Pakistani earthquake of 2006 that killed nearly 75,000 people, as well as the continuing wars in both Afghanistan and Iraq. Nevertheless, disasters can also strike at home and directly in our midst. The destruction wreaked on New Orleans and the Gulf Coast by hurricanes Katrina and Rita and the terrorist bombing of the World Trade Center in New York are ample evidence that no area is immune to both natural and man-made disasters."
> (Dennis Warner, 2006, Senior Technical Advisor, Water Supply, Sanitation and Water Resources Development Catholic Relief Services)

Disasters are extreme events affecting the welfare of populations by causing loss of life, environmental pollution and destruction of property. Hurricane Katrina was the most destructive natural disaster in American history, killing more than 1500 people and laying to waste 90,000 square miles of land - an area the size of the United Kingdom. Estimated property damage approached the $100 billion mark as almost 300,000 homes were completely destroyed or made uninhabitable. (Report of the Senate Committee on Homeland Security and Governmental Affairs 2006) This catastrophe prompted comprehensive review of disaster response system at all levels of government (Federal, State, and Local), the private sector and various other organizations, and reminded everyone that the disaster response system should be reviewed and updated continuously.

Various worldwide organizations continually struggle to assist an increasing number of people affected by natural or man-made disaster causing economic losses, injuries and even fatalities. Each year humanitarian relief organizations respond to as few as 20 and as many as 50 crises caused by natural or political conflict. The number of agencies responding to each crisis varies greatly depending on the need. (Kehler 2004) International relief organizations are making an effort to improve their disaster management techniques to help them operate efficiently when dealing with disaster prevention and victim assistance.

Various organizations have explored many of the management issues involved in humanitarian or disaster relief and published plans or manuals offering practical guidance to humanitarian workers. The National Response Plan (NRP) provides guidance on domestic incident management activities including prevention, preparedness, response, and recovery. The Sphere handbook, designed for use in disaster relief operations, provides a set of minimum standards for several key areas of disaster assistance: water supply and sanitation, nutrition, food aid, shelter and health services (Sphere Project 2004). The effective management of humanitarian assistance activities presents several specific challenges: (Beamon 2004)

- Short (sometimes zero) lead times, dramatically affecting inventory availability, procurement, and distribution
- High stakes (often life-and-death)
- Unreliable, incomplete, or non-existent supply and transportation information
- Ad hoc relief operations without effective performance measures
- Varying levels of available enabling technology (Thomas 2003)

1.2 Problem Statement and Methodology

1.2.1 Problem statement

One of the most important and essential components of relief operations is the allocation of scarce resources to accomplish the relief efforts. Each disaster relief operation needs various critical resources including (but not limited to) personnel, equipment, supplies, or simply finances. Several research efforts for disaster relief have suggested methods to allocate scarce resources across a variety of competing objectives and programs in a disaster relief operation. The goal of the resource allocation problem (RAP) could be maximizing profits, minimizing costs, or achieving the best possible quality (Osman et al. 2005) and a variety of optimization techniques can be employed to solve particular aspects of RAP. Although much effort has been invested in the effective allocation of resources for humanitarian or disaster relief, the lack of clear organizational values or criteria for decision-making contributes to inconsistency in practice and hinders effective resources allocation across the disaster relief system.

While a considerable amount has been written about the methodological and technical issues, very little has been offered on resources allocation based on the decision-makers' or organizations' values in a specific relief operations environment. Much of RAP research focused on optimizing a mathematical programming subject to budget constraints. The link between decision-makers values and resource allocation is relatively under explored.

Related to this, there is no agreed-upon method for comparing the severity of different situations and prioritizing a set of resources accordingly. The models used for humanitarian relief operations must take into account their multi-faceted nature and the basic causal interrelations between the different facets, including the relationship between food aid, water supply, sanitation, nutrition, shelter, health services, safety and security. Assessments in each area should be conducted and coordinated in a manner that reflects these interrelations.

The purpose of this study is to understand the details of humanitarian relief and to develop an integrated multi-objective decision-making (MODM) model to incorporate all of the complex factors in a RAP for disaster relief operations.

Specific objectives of this research include:

- Identifying the values, criteria and measures related to humanitarian relief
- Developing the sequence of steps in the multi-objective decision-making process
- Developing a model that is able to be clearly interpreted by decision-makers and will help the decision-makers make quality decision for resources allocation

1.2.2 Methodology

This research describes the use of (MODM) tools to qualitatively and quantitatively assess the complex and confusing decision problems associated with resources allocation in a disaster relief setting. There are a large number of competing and conflicting objectives in the initial disaster relief operations. As Eilon et al. (1988) point out, it is difficult to quantify the comparative value of competing objectives for selecting and allocating the resources and it is required that there will be some measures of agreement between the different interest groups. MODM captures this agreement in the objective weighting scheme. Therefore, MODM is the most suitable method for dealing with RAP in complicated humanitarian or disaster relief operations.

The aim of the MODM process is to provide a structured method to examine the decision and to develop the subjective judgments that are critical for good decisions. A key to good decision-making is to employ a structured method for incorporating the information, opinions, and preferences of the various relevant people into the decision analysis process (Kirkwood 1997). In this research, the value focused thinking (VFT) process is used to capture the decision-maker(s) values and value trade-offs. A mathematical programming (MP) model that maximizes attainment of the decision-makers values is used to solve the RAP.

1.3 Research Approach

When a disaster occurs, relief efforts should be accomplished and concentrated during the initial hours after damage assessment to deliver any immediate assistance necessary as well as prevent the damage from spreading. Damage assessment is the process of determining the location, nature, and severity of damage sustained by the public and private sectors in a disaster situation. Damage assessment should be carried out as soon as possible after a disaster occurs, while addressing any life-threatening or other critical needs. The accurate information obtained by initial assessment allows decision-maker(s) to identify what resources are needed and to allocate those resources on a priority basis. Resources should be allocated to appropriate locations at the proper time to yield the maximum desired effect. However, available resources are usually limited and there are many restrictions to allocating resources in disaster relief. This research will focus on developing a model to provide an optimal allocation of resources in a relatively short time to maximize relief efforts when a disaster occurs. To accomplish this goal, this research develops a model for efficient resources allocation based on a hurricane and flood scenario. The decision window for the resource allocation is the first 72 hours after the initial damage assessment has been made.

1.4 Thesis Outline

The remainder of the thesis is organized into four chapters. Chapter 2 presents a literature review covering the general problems, required tasks and minimum standards for all sectors of humanitarian relief including: water, sanitation, hygiene promotion, food, shelter and health. Next, a review of the MODM process is provided. Chapter 3 focuses on the development of the decision-making process consisting of VFT process to capture the decision-maker(s) values and value trade-offs and a MP model to find a resource allocation that maximizes the decision-maker values. Chapter 4 describes a case study to demonstrate the process and presents some computational results to validate the MP model. Finally, Chapter 5 provides conclusions, the contributions of the research, unresolved issues, and possibilities for future extensions.

2. Literature Review

This chapter reviews the literature regarding humanitarian or disaster relief and the multi-objective decision-making (MODM) process. The chapter begins with a review of the general concepts of disaster, disaster response, and the minimum standards in each sector of relief and ends with an overview of MODM and decision analysis process.

2.1 General Concepts of Disaster

Today, the United States and many parts of the world are at significant risk of natural and technological disaster. The extraordinary natural, climatic, geographic diversity and contrary effects of modern industrial practices expose the world to a wide range of natural hazards and serious technological disasters. (SDR report 2003) These types of natural hazards and disasters continue to impact the lives of people all around the world. Despite the various efforts of governmental and non-governmental agencies in mitigations, disasters continue to pose a threat to people because of unpredicted factors, precarious economical developments, careless human actions, or a combination of the three.

2.1.1 Definitions

A disaster is the result of a hazard event involving injury or loss of human life, damage or loss of property, or disruption of economic activity. Hazard is a naturally occurring or human-made phenomenon that may result in a disaster when occurring in a populated, commercial, or industrial area. (SDR report 2003) A disaster is also defined as any event that exceeds the capacity of individuals or organizations affected to alleviate their suffering or meet their needs without outside assistance (Gwen 2004).

2.1.1 Types of Disasters

Underlying causes of disasters include natural phenomena, technological catastrophes, and complex humanitarian emergencies (referred to as sociopolitical crises); these are presented in Table 1. Complex humanitarian emergencies are often complicated due to combinations of two or more disastrous events. For example, a war may make groups of a population flee to a neighboring country which may already be in the midst of a natural or technological disaster with large numbers of internally displaced people looking for a safety environment as refuge. (Gwen 2004)

Table 1. Types of Disasters (Gwen 2004)

Natural disasters	Technological disasters	Complex humanitarian emergencies
Earthquakes	Explosions	War
Floods	Fires	
Volcano eruptions	Chemical exposures	Displaced populations
Tornados	Radiation	
Typhoons	Building collapse	Economic disruption
Insect infestation	Transportation accidents	
Landslides		
Drought		
Epidemics		

2.2 Disaster Response

Generally, disaster response can be divided into several stages. The criteria for defining a stage are different for each expert, relief organization and governmental agency. However, it is clear that post event disaster response occurs in short-term and long-term phases. Search and rescue, mass care, damage assessment, public information, temporary housing, utility restoration, and debris clearance are essential elements of short-term response, while repairing or replacing roads, bridges, homes, and stores, strengthening building codes, changing land use, improving transportation corridors, and replacing affordable housing stock are considered long-term response. (Natural Hazards Center 2005) Occasionally, short and long term responses will need to be undertaken concurrently to maintain and enhance quality of life elements (presented in Table 2) - the goal in relieving an affected community from disaster.

Table 2. Quality of Life Elements in Disaster Response Period (Natural Hazards Center 2005)

Element	Description
Housing	Home ownership, affordable homes and rental properties, appreciating property values
Education	Adequate and safe public education
Mobility	Transportation alternatives and efficient flow of traffic
Health Care	Access to high-quality and affordable health care facilities and services
Employment	Suitable job opportunities and low unemployment rates
Economics	Economic vitality, affordable products and services, local business owners, vibrant downtowns and business districts
Recreation	Well-designed public spaces, open spaces, parks, greenways, and recreational facilities.
Environment	Minimal pollution, healthy ecosystems, and resource and energy efficient residential and commercial buildings
Public Safety	Little exposure to crime, diseases and disasters
Equity and Civic Engagement	Ability for residents, community groups, and the private sector to participate in planning and development efforts
Disaster Resilience	Housing, employment, transportation, and public facilities that are protected from or able to withstand impacts of natural hazards

When disaster occurs, the primary response efforts are focused on addressing the immediate needs of the affected population. However, gathering of precise and adequate information for determining initial responses cannot be ensured due to the limited time available to make such an assessment. Therefore, damage and need assessment should be conducted by well-trained staff using suitable methods as soon as possible after a disaster has occurred. Damage assessment is a process for information collection and analysis on a disasters' impact in the public and private sectors. It includes estimating the loss of human life and damage to the economy, environment and infrastructures. (National Response Plan 2004) After damage and need assessment, suitable disaster response activities are determined. Disaster response activities (presented in Table 3) must be based on the extent of damage and the capacity of existing services to provide the resources to meet the needs. The initial disaster response includes: (Gwen 2004)

- Immediate life saving: search and rescue, medical first aid (JWP 3-52 2002)
- Providing basic needs: shelter and clothing, nutritional food and safe water
- Provision of basic health care services to attend to emergency care
- Surveillance and monitoring as part of establishing a health information system to manage epidemiologic data, evaluate effectiveness of treatments, and adapt to priorities
- Organization of human resources as appropriate in a managed disaster response
- Coordination of planning and service delivery activity between all level of government to facilitate communication and to minimize duplication of services

Timely and suitable initial response can minimize losses for human and property as well as limit the cascading and collateral effects caused by a disaster. Therefore, initial response can be considered more critical than recovery or developmental response.

Table 3. Disaster Response Activities

(International Federation of the Red Cross and Red Crescent Societies 2000)

Emergency needs assessment	Shelter
Reliable communication systems	Security
Warning and notification systems	Water and sanitation
Logistics	Food and nutrition
Transportation	Other household needs
Emergency medical care	Family reunification

2.3 Minimum Standards in Each Sector

Disaster relief operations must be based on a clear understanding of the situation. Initial damage assessments will analyze the disasters' impact on human life, economy and environment, and its effect on the population. At the same time, resources needed to recover from damages caused by the disaster should be identified. Resources are not simply manpower to carry out response activities but also other essentials such as facilities, equipment, food, clean water, necessities, tents, etc. to serve the needs of the population.

In many situations, damage and needs information may not be available due to characteristics of the disaster relief environment (i.e. the area may be inaccessible for some amount of time immediately following the disaster) which would hinder the ability of relief agencies to respond appropriately. In such situations, minimum standards may be used as a guideline for identifying relief goals and needs in each sector. The handbook published by the Sphere Project (2004) provides minimum standards in the main four sectors: 1) food security, nutrition and food aid; 2) water supply, sanitation and hygiene promotion; 3) shelter, settlement and non-food items; and 4) health services. Because they depend upon various factors such as type and magnitude of the disaster, available resources, and short- and long-term relief stages, etc., these standards may not be applicable to every disaster relief circumstance. There are also several additional objectives which should be considered such as search and rescue, transportation, communication, public safety and security, etc. Nevertheless, the minimum standards suggested by the Sphere handbook provide a basis for identifying and gathering essential elements and resources for initial relief efforts. Chapter 3 reviews the key sectors of relief operations and uses those sectors as the basis for the multiple objectives to be addressed with the limited resources for disaster relief.

2.3.1 Food Security, Nutrition and Food Aid

Adequate food supply and the maintenance of nutritional status are critical determinants of people's survival in a disaster. Malnutrition can be the most serious public health problem and a leading cause of death, either directly or indirectly. (The Sphere Project 2004) Figure 1 presents the minimum standards for food security, nutrition and food aid. Therefore, feeding operations should be based on nutritional standards to include meeting requirements of victims with special dietary needs to the greatest extent possible (NRP 2004). In addition, relief organizations should consider the various kinds of people affected by the disaster who are in need of food. People with damaged housing, evacuated individuals and isolated travelers, as well as relief workers will all require food aid.

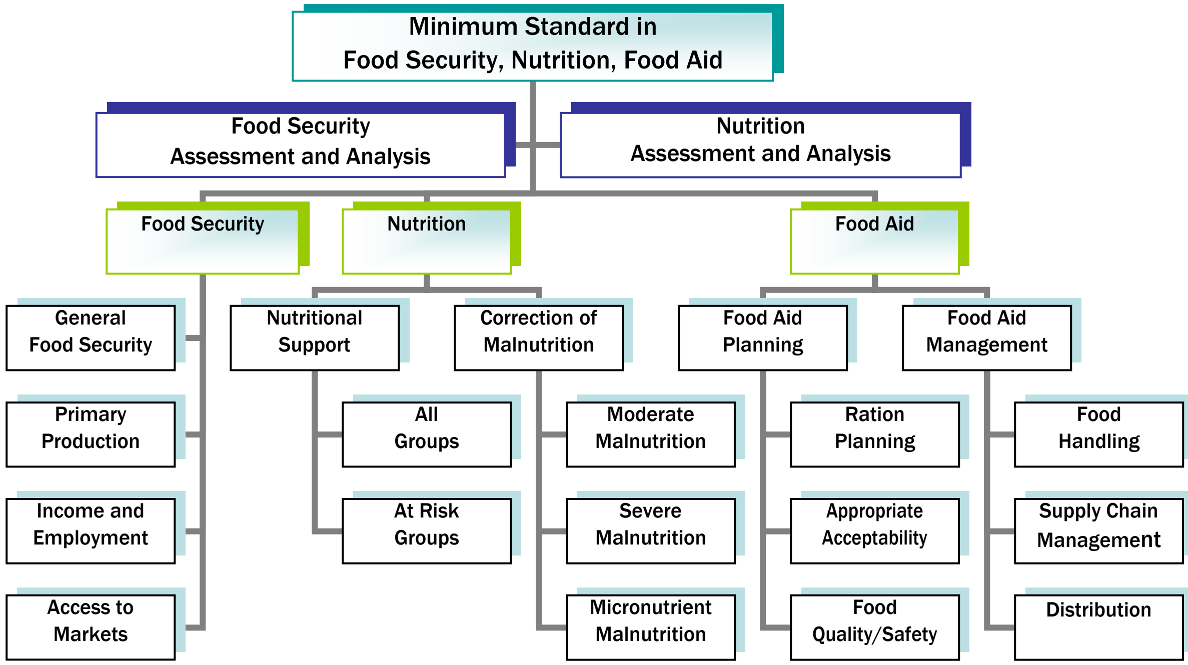


Figure 1. Minimum Standard in Food Security, Nutrition and Food Aid (The Sphere Project 2004)

2.3.2 Shelter, Settlement and Non-Food Items

Shelter is also a critical determinant in the initial disaster response. Shelter is necessary to provide security and personal safety, protection from the climate and enhanced resistance to ill health and disease (The Sphere Project 2004). Figure 2 presents the minimum standards for shelter, settlement and non-food items. Shelter includes the use of pre-identified shelter sites in existing structures, creation of temporary facilities or the temporary construction of shelters, and the use of similar facilities outside the disaster area (NRP 2004). If the disaster is predicted, sheltering operations will begin prior to its occurrence when information and various media outlets warn the large-scale evacuation of people is inevitable.

Non-food items, such as clothing, bedding, and household items, are also essential elements to reduce suffering and overcome short- or long-term effects of a disaster. Non-food assistance should be available until families or individuals can return to their homes.

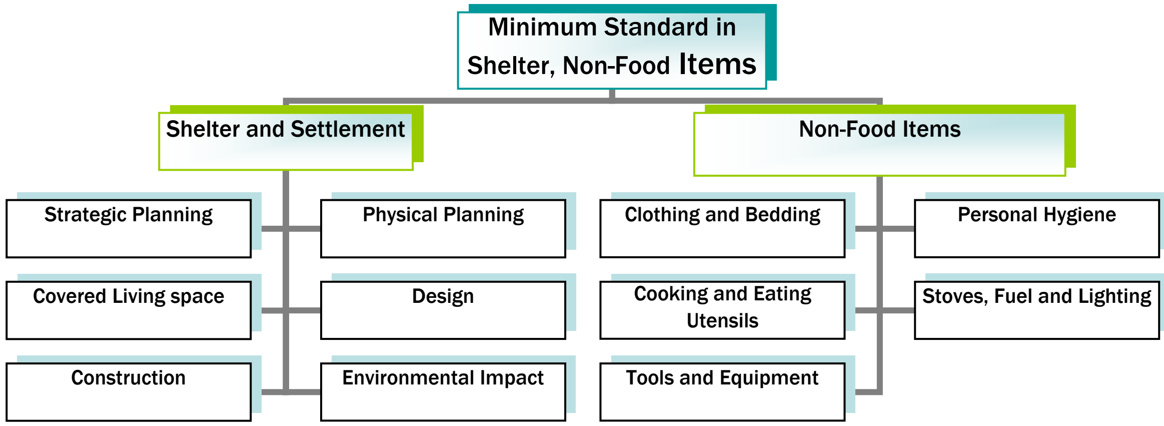


Figure 2. Minimum Standard in Shelter, Settlement and Non-Food Items (The Sphere Project 2004)

2.3.3 Water, Sanitation and Hygiene Promotion

Water supply for drink, sanitation, and hygiene improvement are also critical determinants for survival in the initial stages of a disaster. People affected by disasters are generally much more exposed to illness and death from diseases, which can be a result of inadequate water supplies, sanitation, and poor hygiene. (The Sphere Project 2004) Figure 3 presents the minimum standards in water, sanitation, and hygiene. The objective of water supply and sanitation programs in disaster relief is not only to provide nourishment for the people and enhance quality of life, but also to reduce the transmission of an epidemic. The control of the spread of infectious diseases is one of most challenging problems in a disaster relief environment. Providing adequate safe water and resources for sanitation such as latrines, soap, detergents, chlorine powder and insecticides sprayers can significantly reduce the health risk.

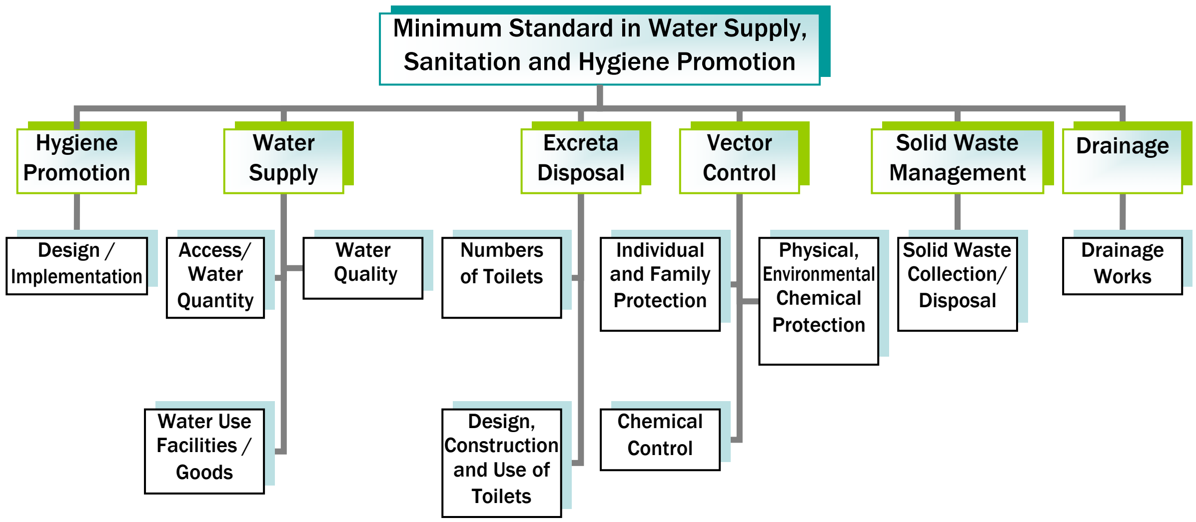


Figure 3. Minimum Standard in Water Supply, Sanitation (The Sphere Project 2004)

2.3.4 Health Services

A significant disaster may cause injuries to a considerable number of people and create widespread need for medical care or public health guidance (NRP 2004). Health services are closely related to the primary goals of disaster relief which are prevention and reduction of mortality and morbidity, and promotion of a return to normalcy. Figure 4 presents the minimum standards for health services. Initial relief efforts should be concentrated on the evaluation and analysis of public health and need for medical assistance. Different types of disasters are associated with differing scales and patterns of mortality and morbidity (presented in Table 4), therefore the public health and medical service will vary according to the type and extent of disaster. (The Sphere Project 2004) However, in the early stages of the disaster, it may not be possible to fully assess the situation and verify the level of assistance required. In these cases, every reasonable attempt is made to verify the need before providing assistance and medical facilities, hospital wards, casualty rooms, operating theaters, and laboratories should be ready for care and treatment of patients before the disaster occurs (NRP 2004).

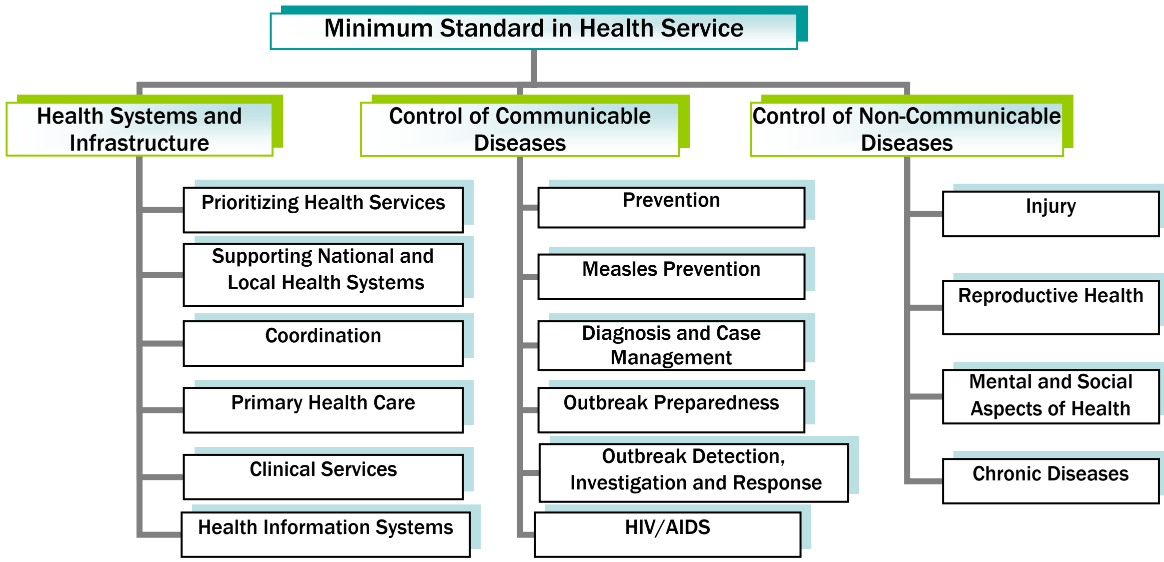


Figure 4. Minimum Standard in Health Service (The Sphere Project 2004)

Table 4. Public Health Impact of Selected Disasters

(Sphere Handbook adapted from Pan American Health Organization 1981)

Effect	Complex Emergencies	Earthquakes	High Winds (w/o Flooding)	Floods	Flash floods/ Tsunamis
Deaths	Many	Many	Few	Few	Many
Severe injuries	Varies	Many	Moderate	Few	Few
communicable diseases	High	Small	Small	Varies	Small
Food scarcity	Common	Rare	Rare	Varies	Common
Population displacements	Common (may occur in heavily damaged urban areas)	Rare	Rare	Common	Varies

2.4 Multi-Objective Decision-Making (MODM)

Given the complexity of life today, most important decisions require a multiple objective approach. Some decisions may be made considering a single criterion, but these are usually limited to the relatively simple ones. Very few decisions of significance can be made based on only single criterion. Given these conditions, the two terms "multi-objective" and "decision-making" are nearly inseparable, especially when making complex decisions that require consideration of all the different aspects that affect the decision.

2.4.1 Definitions and Concepts

Decision-making is the process of arriving at a determination based on consideration of available alternatives (Kirkwood 1997). MODM involves making a decision based on more than one criterion. Criteria are the rules, measures, and standards that guide decision-makers. Since decision-making is conducted by selecting or considering key attributes, objectives, or variables, all these elements can be referred to here as criteria. That is, criteria are all those attributes, objectives, or variables which have been judged relevant in a given situation by a particular decision-maker. (Saaty 1991)

Objectives are statements of something that one desires to achieve. Generally, objectives are characterized by three features: decision context, objectives, and direction of preferences. Objectives can be either fundamental objectives or means objectives. Fundamental objectives characterize an essential reason for interest in the decision situation and means objectives are of interest in a decision context because they are a means of achieving fundamental objectives. (Keeney 1992)

An attribute indicates the level to which the objective is achieved in the alternative. The possible outcomes of the attribute are referred to as performance levels. When a performance level is associated with a certain alternative, the term consequence is used instead (Raimo et al. 2002). Attributes $x_1, x_2, ..., x_n$ create a mapping from the act space *A* into the *n* dimensional consequence space. For a decision alternative *a* in *A*, the corresponding point in the consequence space is expressed as

$$X(a) = (x_1(a), x_2(a), ..., x_n(a)) = (x_1, x_2, ..., x_n)$$

The situation where *n*=3 is illustrated in Figure 5 (Raimo et al. 2002)

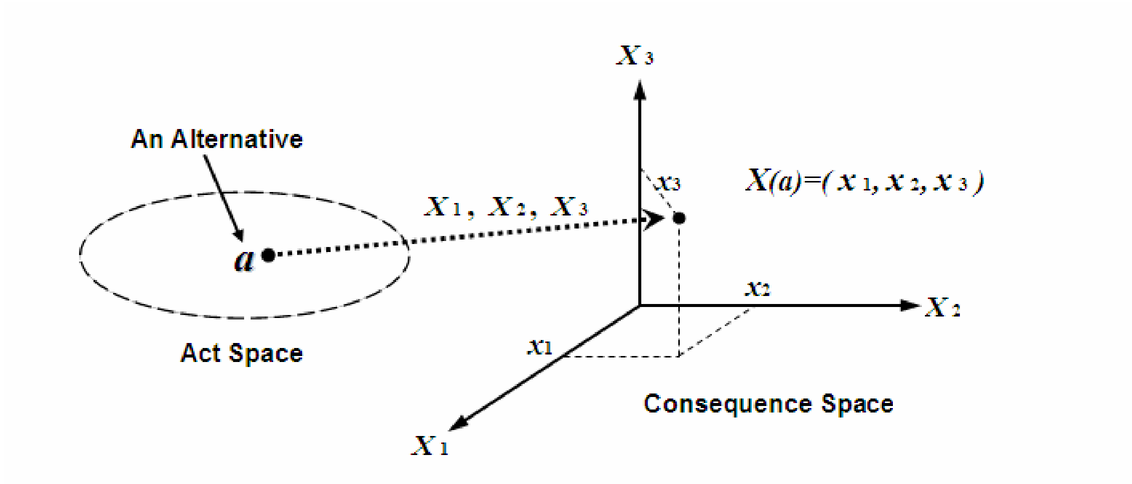


Figure 5. The Mapping of Alternatives to the Consequence Space

2.4.2 Multi-Objective Decision Analysis (MODA)

Decision analysis is a process for systematically analyzing complex decision problems. This process includes dividing the decision problem into smaller more understandable parts, analyzing each part, and integrating the parts in a logical manner to produce a meaningful solution (Malczewski 1999). The aim of the process of decision analysis (DA) is to provide a structured methodology to examine decisions and develop and support subjective judgments that are critical for good decisions. (Raimo et al. 2002) In general, MODA problems involve six components (Keeney and Raiffa 1993):

- The decision-maker or a group of decision-makers involved in the decision-making process along with their preferences with respect to the evaluation criteria
- A goal or a set of goals the decision-maker(s) want to achieve
- A set of evaluation criteria (objectives and / or physical attributes)
- The set of decision alternatives
- The set of uncontrollable (independent) variables or states of nature
- The set of outcomes or consequences associated with each alternative

MODA techniques can be used to identify a single most preferred option, to rank options, to list a limited number of options for subsequent detailed evaluation, or to distinguish acceptable from unacceptable possibilities (Dodgson 2000).

2.4.3 Value Focused Thinking (VFT)

With respect to humanitarian or disaster relief, various peoples, agencies, decision-maker(s) and government officials (each having different perspectives and objectives in each sector) must work together. Relief operations are very complex and require consideration of numerous factors. Multi-objective decision analysis (MODA) is a popular method for solving problems with multiple considerations (Hung et al. 2005). The main method applied in this research is VFT which is a MODA technique that focuses on what individuals or organizations value to identify the most important objectives in disaster relief. VFT concentrates on determining the values at the core of the decision rather than having the decision-maker(s) choose between predetermined lists of alternatives. A deep and thorough understanding of the values inherent in a decision situation can provide important insights for all aspect of decision-making, and these insights make it possible to achieve much better consequences for the decision at hand. (Keeney 1992) The influence of VFT on the decision-making process is illustrated in Figure 6.

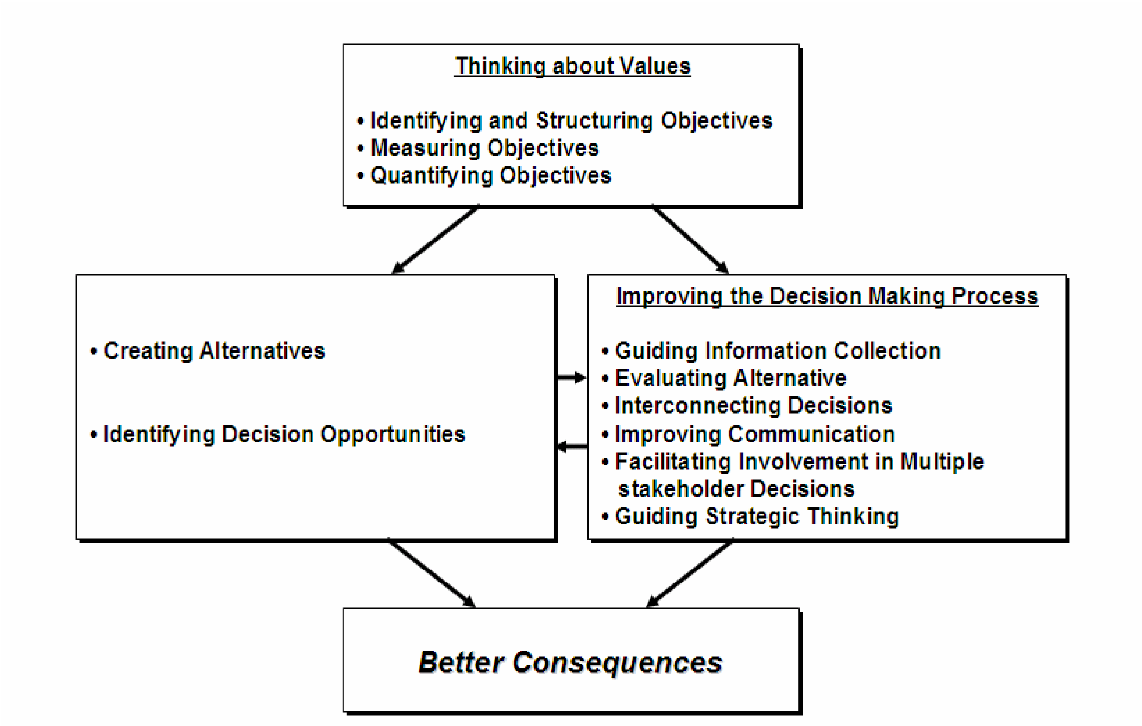


Figure 6. The Influence of VFT on the Processes of Decision-making (Keeney 1992)

VFT process can be developed through several steps the basis for the value model within this research. The following steps (Keeney 1992, Raimo et al 2002, Clemen 2001) assist in information collection and facilitate communication between the decision maker and the analyst.

(1) Problem Identification

The main purpose of problem identification is to create a better understanding of the decision problem. Careful identification of the decision at hand is always important. (Clemen 2001) In this step, the general approach is to first understand the values and objectives and then look for decision opportunities. After the decision situation and real nature of the problem is established, objectives and possible decision alternatives are identified.

Decision context is the setting in which the decision occurs. In Figure 7, main factors and questions specifying the decision context are shown. Decision context and corresponding fundamental objectives are closely related and frame the decision situation. By defining the decision context and establishing the nature of the decision problem carefully, the treatment of the real problem can be ensured. (Raimo et al. 2002)

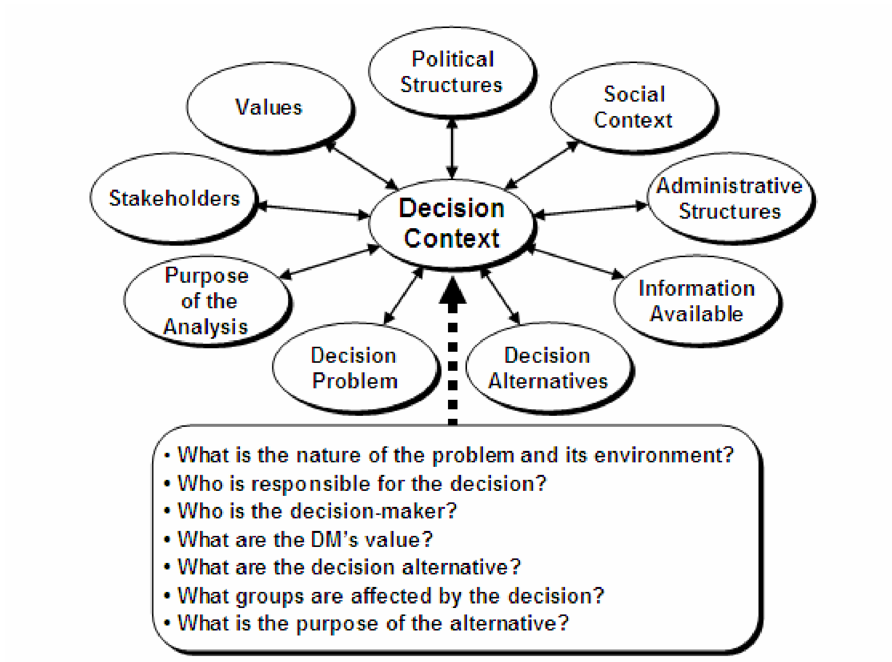


Figure 7. Decision Context (Raimo et al. 2002)

(2) Objectives Identification

Identifying objectives is also an important first step which requires significant creativity and focused thinking (Keeney 1992). An analyst often has an important role as a facilitator in guiding and stimulating the process. An obvious method to identify objectives is to ask a group of decision-makers or stakeholders to first reiterate the decision context, individually provide a written list of objectives, and discuss the lists as a group (Keeney 1992; Raimo et al. 2002). Several techniques (presented in Table 5) can be used to stimulate the identification of possible objectives (Keeney 1992).

Table 5. Techniques to Use in Identifying Objectives (Keeney 1992)

1. A wish list

What do you want? What do you value? What should you want?

2. Alternatives

What is a perfect alternative, a terrible alternative, some reasonable alternative?
What is good or bad about each?

3. Problems and shortcomings

What is wrong or right with your organization? What needs fixing?

4. Consequences

What has occurred that was good or bad? What might occur that you care about?

5. Goals, constraints, and guidelines

What are your aspirations? What limitations are place upon you?

6. Different perspectives

What would your competitor or your constituency be concerned about?
At some time in the future, what would concern you?

7. Strategic objectives

What are your ultimate objectives? What are your values that are absolutely fundamental?

8. Generic objectives

What objectives do you have for your customers, your employees, your shareholders or yourself? What environmental, social, economic, or health and safety objectives are important?

9. Structuring objectives

Follow means-ends relationships: Why is that objective important? How can you achieve it?
Use specification: what do you mean by this objective?

10. *Quantifying objectives*

How would you measure achievement of this objective?
Why is objective A three times as important as objective B?

In addition to discussions with decision-makers, several other approaches can be taken to generate objectives: (Keeney and Raiffa 1976; Raimo et al. 2002)

• *Examination of the relevant literature:* by studying problems similar to the one under consideration, relevant objects may be found.

• *Analytical study:* by building a model of the system under consideration and identifying relevant input and output variables, suitable objectives may become obvious.

• *Casual empiricism:* objectives may be generated by observing people who are making decisions that are relevant to the problem

• *Surveys*

• *Expert panel:* a group of people with expertise in the area may be used to generate the objectives

(3) Hierarchical modeling of objectives

The process of the structuring and hierarchical modeling of the objectives results in a deeper and more accurate understanding of what one should care about in the decision context (Keeney 1992). Hierarchical modeling of objectives can be performed by the following steps (Raimo et al. 2002):

• *Separating means from fundamental objectives*: As the major goal of the objective generation process is to produce an exhaustive list of objectives, they are likely to be inconsistent and changeable in their scope, explicitness and detail. For that reason it is important to separate fundamental objectives from means objectives. Fundamental and means objectives have different roles in the analysis. Fundamental objectives characterize the reason for interest in a decision situation, and thus are essential part of the problem structuring. Means objectives are helpful for creating alternatives and developing models to analyze the decision problem.

• *Objectives structures*: Both fundamental and means objectives are often displayed in objective structures. The distinctions between the objective structures are shown in Table 6 (Keeney 1992). In this research, the term value hierarchy (tree) refers to the fundamental objectives hierarchy and attributes associated with it.

Table 6. Comparison of Fundamental and Means Objective Structures (Keeney 1992)

Structure	Characteristics
Fundamental Objectives Hierarchy	• The hierarchy includes only fundamental objectives • A higher-level objective is defined by the set of lower-level objectives under it • Within any set, the lower-level objectives are mutually exclusive and provide an exhaustive characterization of the higher-level objective • Every higher-level objective has at least two lower-level objectives connected to it
Means-ends Objectives Network	• The network may include both fundamental and means objectives • A lower-level objective is a means to the higher-level objectives • The set of means objectives under a higher-level objective does not necessarily provide an exhaustive representation of the means leading to the higher-level objective • Higher-level objective may have only one lower-level objective connected to it

• *Constructing value hierarchy*: There are two methods to construct value hierarchy. The first method is a top-down approach which begins with the most general objective, which is then successively divided into sub-objectives. The other method is bottom-up approach. In a bottom-up approach all meaningful differences between alternatives are first listed and then combined and structured to higher level objectives. Generally, the top-down approach is the preferred and most suitable method to construct a fundamental objectives hierarchy and the bottom-up approach is most appropriate to generate a means-ends objectives network.

The steps of the top-down approach are as follows: 1) Identify the overall fundamental objective, 2) Specify and clarify the intended meaning of the objectives in terms of more specific objectives (the analyst can ask the decision-maker(s) to state what aspects of the higher-level objectives they consider as important), and 3) Subdivide the objectives until the lowest level is sufficiently well defined such that a measurable attribute can be associated with it.

• *Checking the hierarchy*: When constructing the value hierarchy the analyst should check that: 1) The division of an objective into lower-level objectives is reasonable, 2) The set of lower level objectives should be unique to the upper-level objective, and 3) The set of objectives is essential. That is, each of the alternatives included in the decision context can influence the degree to which the objectives are achieved. (von Winterfeldt and Edwards 1986; Keeney 1992) Kirkwood (1997) also describes several desirable properties for a value hierarchy:

• *Completeness*: All relevant objectives should be included in the hierarchy. The set of attributes completely defines the degree to which the overall objective is achieved.

• *Non-redundancy*: The set of attributes should be non-redundant to avoid double counting of the consequences – similar to 2 above.

• *Decomposability*: Attributes should be judgmentally independent, that is, it should be possible to analyze one attribute at time.

• *Operability*: Attributes should be meaningful and assessable. An operable value hierarchy is one that is understandable for the persons who must use it.

• *Small size*: The set of attributes should be minimal. A smaller value hierarchy can be more easily communicated to interested parties and requires fewer resources to estimate the performance of alternatives with respect to the various evaluation measures.

(4) Development of Evaluation Measures (attribute scale)

The degree to which objectives are achieved in different decision alternatives is measured with attributes. There are four characteristics of attributes scales. (Keeney 1992; Kirkwood 1997; Raimo et al. 2002)

• *Natural vs Constructed*: Natural attributes can be measured in natural scale (i.e. centimeters, dollars, numbers, etc.) and have a common interpretation by everyone. Constructed attributes do not necessarily have a common interpretation. In most cases they are developed for a given decision context. Constructed scales are used in a variety of situations where natural scales are not appropriate. The careful development of constructed attributes scales, with the clarification of the value judgments that are essential to that attribute, may promote thinking and describe the consequences in a decision situation much better than the natural attributes scales.

• *Direct vs Proxy*: Direct attributes directly measure the degree of attainment of objectives, while proxy attributes reflect the degree of attainment of its associated objective without directly measuring the objectives. Proxy attributes should be valued only for their perceived relationship to the achievement of the corresponding fundamental objective. For example, a relief operation may have the objective of "effective and efficient medical care assistance". For such an objective, it is difficult to find direct measure. However, "number of patients treated and released per hour" may be used as a proxy attribute to measure indirectly the effectiveness of medical care assistance.

In general, natural is preferred to constructed and direct to proxy. Analysts choosing natural-direct scales are not required to spend time developing the scale definition. However, natural-direct scales are not all that easy to determine, thus, natural-proxy or constructed-direct scales may be required for evaluation consideration. (Kirkwood 1992)

Desirable properties of attributes include comprehensiveness, understandability and measurability. Comprehensiveness and understandability imply that no ambiguity exists in describing the level of which an objective is achieved in terms of an attribute. Measurability means that it is possible to assess the decision-maker's preferences for different levels of the attribute and measuring the decision-maker's preferences can be accomplished without excessive amount of time, money and effort. (Raimo et al. 2002)

(5) Create Value Functions

To conduct a multi-objective value analysis, it is essential to elicit a value function, which combines the multiple attributes into a single measure of the overall value of each alternative (Kirkwood 1997). The purpose of the value function elicitation is to model and describe the importance and desirability of achieving different performance levels of the given attribute (Raimo et al. 2002). To ensure competing objectives are measured proportionally on the same scale, individual evaluation measure scales must be converted to common scores with value between 0 and 1.

Generally, there are two different procedures for determining a value function. One of these procedures results in a single dimensional value function (SDVF) that is made up of segments of straight lines that are joined together into a piecewise linear function, while the other elicitation uses an exponential form the SDVF. When the value measure has small number of possible different scoring levels, a piecewise linear function is generally used. (Kirkwood 1997)

(6) Weight Value Hierarchy

The additive value model is a simple model in which the value of an alternative is determined by taking a weighted sum of the levels of attainment for each attribute. In the additive value model, each evaluation measure within the hierarchy is weighed based on relative importance and variation. (Merrick et al. 2005) The purpose of weighting the value hierarchy is to identify the importance each value contributes to the overall goal or problem. Since value functions range from 0 to 1, the weight is the change in the additive value function as the evaluation measure changes from the worst to the best level. In most cases, the weights are normalized, in such a way that the sum of the weights equals 1. Weights of the objectives are used when interpreting the results of the analysis. (Raimo et al. 2002)

(7) Sensitivity analysis

Sensitivity analysis in a DA process answers the question: "what makes a difference in this decision?" It is used to examine how robust the choice of an alternative is to changes in the figures used in the value hierarchy; it shows how each alternative changes in ranking as the weight of any higher tier value changes. The weights within the value hierarchy tend to be a major focus of sensitivity analysis since they are often a source of disagreement within the decision-maker groups. (Kirkwood 1997)

2.4.4 Mathematical Programming (MP)

MP methods aim to maximize or minimize an objective function subject to a set of constrains. A MP model can include multiple objectives and be used to quantify the nature of trade-offs among objectives. (Nguyen 2003) The mathematical expression of a MP problem is as follows (Hung et al. 2003; Gabriel et al. 2006; Nguyen 2003):

$$Max\ z(x) = \left[z_1(x), z_2(x), ..., z_k(x), ..., z_m(x)\right]$$

Subject to: $x \in X, x \geq 0$

where $z(x)$ denotes the objective function with m objectives, x represents the set of non-negative decision variables, and X represents the sets of constraints. Each feasible solution implies a value for each objective $z_i(x)$, i=1,…,m. In this research, mathematical programming, especially mixed integer linear programming (MILP), is the method used to find an allocation of limited resources that maximizes the decision-maker(s) value as captured in the value hierarchy.

2.5 Summary

This chapter introduced general concepts of disaster and MODM. The topics reviewed provide a better understanding for the decision problem that this research explores and the methodology that is used. As complex, confusing problems are frequently encountered in disaster relief solving them typically involves consideration of a wide range of criteria. MODM procedures offer a potential approach to address the many difficult problems associated with disaster relief.

In the next chapter, the VFT process is demonstrated in the context of disaster relief. A notional hierarchical organization of objectives and their associated single dimensional (attribute) value functions and weights are created. The chapter concludes with a presentation of a mathematical programming approach for solving the value model.

3. Research Methodology

In this chapter, a value focused thinking (VFT) and mathematical programming (MP) approach to determine resources allocation for initial disaster relief efforts is described. The VFT process provides the value hierarchy containing the fundamental objectives for the initial disaster relief. A MP model is used to determine the resource allocation yielding the maximum decision-maker value. The development of the value hierarchy is described first, followed by the MP formulations.

3.1 Development of the Initial Disaster Relief Value Hierarchy

3.1.1 Identifying and Generating Objectives

Disaster relief is the organized response to alleviate the adverse effects resulting from a catastrophe and aims to save lives and lessen suffering, limit damage and restore essential services to a level that enables local authorities to cope with the recovery. Disaster relief demands the total integration of the relief effort with the life-support assets and infrastructure available within the stricken area. The allocation of resources such as food, water, clothing, medical inventory, and services such as rescue, emergency workers, transportation and necessary equipment is necessary to save lives and prevent physical damage and suffering. (JWP 3-52 2002) The quality of the relief efforts can be improved by an effective use of the available resources.

Many of the resource-related objectives are means objectives that lead to the fulfillment of other fundamental objectives. For example, resource-related objectives such as “increasing available cooking and eating utensils” or “increasing available clothing and bedding” may be important objectives of disaster relief, but they are means objectives under the means objective of "shelter and settlement standard" which in turn addresses the fundamental objectives of "Public Safety" and "Public Health". Fundamental objectives should be identified first as essential elements for the effective relief operation and resource-related objectives can then be retained as means objectives for use in identifying and creating decision alternatives later in the process.

Several techniques can be used to stimulate the identification of the value and generation of the possible objectives. Parnell, et al. (1998) define three standards for developing multi-objective value model: platinum, gold and silver. A *platinum standard* is based on interviews with decision-makers and stakeholders to determine the objectives. A *gold standard* is based on approved vision, policy, strategy, planning, or doctrine documents. A *silver standard* uses interviews with subject-matter experts (SMEs) and data provided by stakeholder representatives. (Merrick et al. 2005) When decision-makers and stakeholders are not available, silver standard is a useful way to identify the values and objectives. (Parnell et al 1998) This research uses the silver standard in conjunction with a review of relevant literature to develop the notional value hierarchy.

3.1.2 Construction of the Value Hierarchy

To develop the notional value hierarchy, various sources (journals, articles, theses and dissertations, government planning documents, manuals and handbooks, etc.) were examined. This research then chose *Maximize Effectiveness of Initial Disaster Relief* as the overall objective. Sub-objectives were identified through *affinity diagrams* and the silver standard method. An affinity diagram is a tool that gathers large amounts of data (ideas, opinions, issues) and organizes them into groupings based on their natural relationships (Parnell et al. 1998). Affinity groups are mutually exclusive and collectively exhaustive, and affinity diagramming has a benefit of often identifying new objectives tailored to the overall objective (Merrick et al. 2005).

After the affinity diagramming procedure, the final value hierarchy was formed. The value hierarchy for initial disaster relief efforts is presented in Figure 8 and may be viewed as the holistic response and recovery plan's collective fundamental objectives of disaster relief. Disaster response can be divided into three stages; 1) immediate life saving phase (search and rescue, medical first aid, etc.); 2) stabilization phase (the delivery of aid); 3) recovery phase (rehabilitation and reconstruction) However, these stages are unlikely to be exclusive and will often need to be undertaken concurrently, which requires a flexible response. (JWP 3-52 2002) Therefore, the value hierarchy includes initial disaster response tasks, recovery and reconstruction tasks, mitigation efforts for preventing secondary damage, and related relief operation concerns that must be accomplished to attain the overall objective.

The value hierarchy contains fundamental objectives which are identified with key sectors of disaster relief. For such a complex decision context, it is difficult to ensure that the value hierarchy contains a complete set of fundamental objectives of disaster relief. When structuring the value hierarchy, there is a trade-off between size and completeness. The amount of analysis required depends on the size of value hierarchy. The various documents, manuals and plans used to construct the value hierarchy have different perspectives on disaster relief and include numerous relief activities. To keep the hierarchy at a reasonable size, all similar activities and tasks are grouped together in single aggregated sub-objective. For example, using affinity diagramming, temporary housing and evacuation are aggregated into a single sub-objective represented by shelter.

Likewise, public health, medical support, medical equipment supplies, casualty and fatality management are combined into health service. In addition, although relief response stages may be undertaken concurrently, long-term recovery and mitigation activities such as building economic vitality, financial management, reestablishment of major transport linkages, employment rates, historic recovery, etc. that are typically accomplished long after initial response were excluded from the value hierarchy.

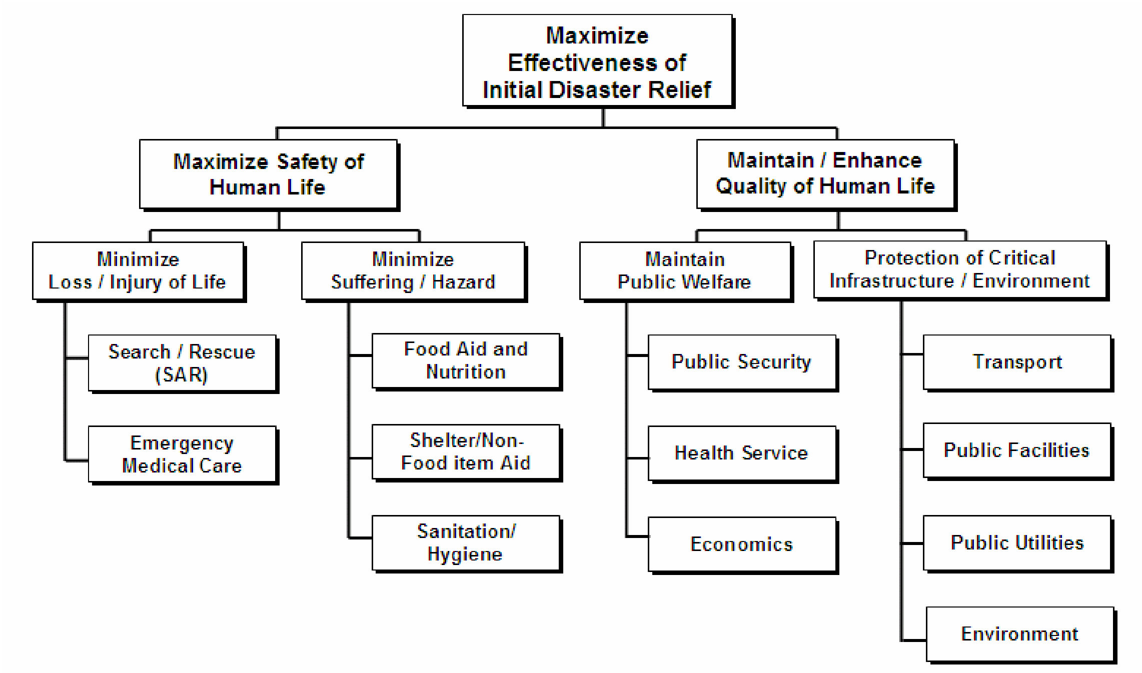


Figure 8. Initial Disaster Relief Value Hierarchy

Figure 8 shows that initial disaster relief is divided into two fundamental objectives: *Maximize Safety of Human Life* and *Maintain / Enhance Quality of Human Life*. *Maximize Safety of Human Life* was divided into two sub-objectives: *Minimize Loss / Injury of Life* and *Minimize Suffering / Hazard*. The former is a direct cause and the latter an indirect cause of death. *Emergency Medical Care* and *Health Service* below *Loss / Injury Life* and *Maintain Public Welfare* respectively, may be considered the same activities; however, for the purposes of this research *Emergency Medical Care* is defined as first-aid for treated the injured, while *Health Service* is defined as public medical care such as patient care, vector control, access to high quality and affordable health care facilities, etc. *Minimize Suffering / Hazard* was divided into three sub-objectives: *Food Aid and Nutrition, Shelter and Non-Food Item Aid,* and *Sanitation and Hygiene*. These are three of the four minimum standard sectors addressed in the Sphere handbook. They could have been aligned under *Maintain and Enhance Quality of Human Life*, but were viewed as essential and therefore more related to the element of public safety and minimizing suffering. The fourth sector addressed in the Sphere handbook is *Health Service* which was placed below *Maintain Public Welfare*.

Maintain / Enhance Quality of Human Life was divided into two sub-objectives: *Maintain Public Welfare*, and *Protection of Critical Infrastructure / Environment*. Disasters create sudden changes to social networks, lifelines, the environment, housing, and the economy and also dramatically affect the health and safety of community residents. For instance, damaged infrastructure causes reduced mobility and access to services. Additionally damaged utilities (power lines, phone lines, water treatment plants, etc.) and facilities (schools, downtown, historic districts, public areas, airports, harbors, power plants, business and telecommunication centers, etc.) can 1) reduce communication, 2) increase threat of disease and safety or security, and 3) affect education, employment, economy, and environment. (Natural Hazard Center 2005) For this research these categories were developed into three and four sub-objectives, respectively. The lowest level objectives (attributes) and their definitions are shown in Table 7.

Table 7. Objectives / Descriptions

Objectives			Descriptions
Maximize Safety of Human Life	Minimize Loss / Injury of Life	Search / Rescue	• Immediate life-saving, extricating assistance ► *Maximize rescue of people in imminent danger*
		Emergency Medical Care	• Providing on-site medical treatment / first aid ► *Minimize mortality of victims*
	Minimize Suffering / Hazard	Food Aid and Nutrition	• Feeding operations based on nutritional standards ► *Maximize provision of food / water to evacuees*
		Shelter/ Non-Food Item Aid	• Welfare assistance to displaced people ► *Maximize provision of emergency housing and stock to evacuees*
		Sanitation/ Hygiene	• Preventing spread of infectious diseases / health risk ► *Maximize provision of sanitary arrangements and stock to evacuees*
Maintain / Enhance Quality of Human Life	Maintain Public Welfare	Public Security	• Little exposure to crime, protecting property / control crowds and traffic ► *Maximize prevention of crime / chaos*
		Health Service	• Providing high quality health care and medical treatment ► *Maximize responses to health care requirement*
		Economics	• Affordable products and services ► *Maximize resident satisfaction with public economical activities in affected area*
	Protection of Critical Infrastructure / Environment	Transport	• Minimal damage and emergency repair / maintain transport function and capability ► *Minimize damage of roads, bridges, subway and related infrastructure in affected area*
		Public Facilities	• Minimal damage and emergency repair / maintain public facilities function and capability ► *Minimize damage of school, downtown, harbor, port, air port, stormwater system, power plant, etc. in affected area*
		Public Utilities	• Minimal damage and emergency repair / maintain public utilities function and capability ► *Minimize damage of power and phone lines, water treatment plant utilities in affected area*
		Environment	• Minimal pollution and protecting ecosystem ► *Maximize prevention of environment damage*

3.1.3 Creation of the Value Function

The next process is the creation of the value function. To conduct a multi-objective value analysis, an additive value function is used to combine measure attainment of each objective. Determining an additive value function requires that single dimensional value functions (SDVFs) are specified for each evaluation measure and weights are specified for each SDVF. The additive value function is a weighted combination of the single dimensional value functions. (Kirkwood, 1997) Since there are twelve measurable attributes in the notional disaster relief hierarchy, the additive value function can be expressed as

$$V(x_1, x_2, ..., x_{12}) = \sum_{j=1}^{12} w_j v(x_j) = w_1 v(x_1) + w_2 v(x_2) + \cdots + w_{12} v(x_{12})$$

where $V(x_1, x_2, ..., x_{12})$ is the value function that allows us to rank alternatives, $v(x_j)$ is the SDVF that converts each evaluation measure x_j to a common value scale, and w_j reflects the weight of each evaluation measure to overall preference (Keeney and Raiffa 1993). The weight w_j corresponds to the change in the strength of preferences as the evaluation measures x_j changes from the worst to the best level. Additive value functions capture the decision-maker's preferences only if the evaluation measures are mutually preferentially independent (Raimo et al. 2002).

3.1.4 Selection of Evaluation Measures

Evaluation measures (also called measures of effectiveness or attributes) are used to measure the degree of attainment of the objectives. The evaluation measures should provide an unambiguous rating of how well an alternative does with respect of each objective (Kirkwood 1997). It is difficult to find appropriate evaluation measures for many humanitarian or disaster relief objectives. There are no all-encompassing manuals for evaluating disaster relief operations. Thus, careful development of constructed or proxy evaluation measures is needed. The overall objective was divided into two sub-objectives, or first tier objectives, and these were further divided into lower level sub-objectives. The lowest tier objectives of a hierarchy are evaluated. There are twelve lowest-tier objectives in the notional disaster relief operations value hierarchy. An evaluation measure is developed for each of them in the following paragraphs.

Prior to developing evaluation measures, it is helpful to know the range of attainment for the objectives. This range is a function of the alternatives to be evaluated; thus, some alternatives should be generated prior to determining the evaluation measures. The value hierarchy provides a framework for generating alternatives. The initial disaster relief value hierarchy (Figure 8) contains the decision-maker(s) and stakeholders' values. The lowest level sub-objectives should have relationships with various alternatives associated with relief resources. As reviewed previously, resource-related objectives are mostly means objectives and are retained for use in identifying decision alternatives (Keeney 1992). Figure 9 shows value hierarchy combined with the resource-related objectives.

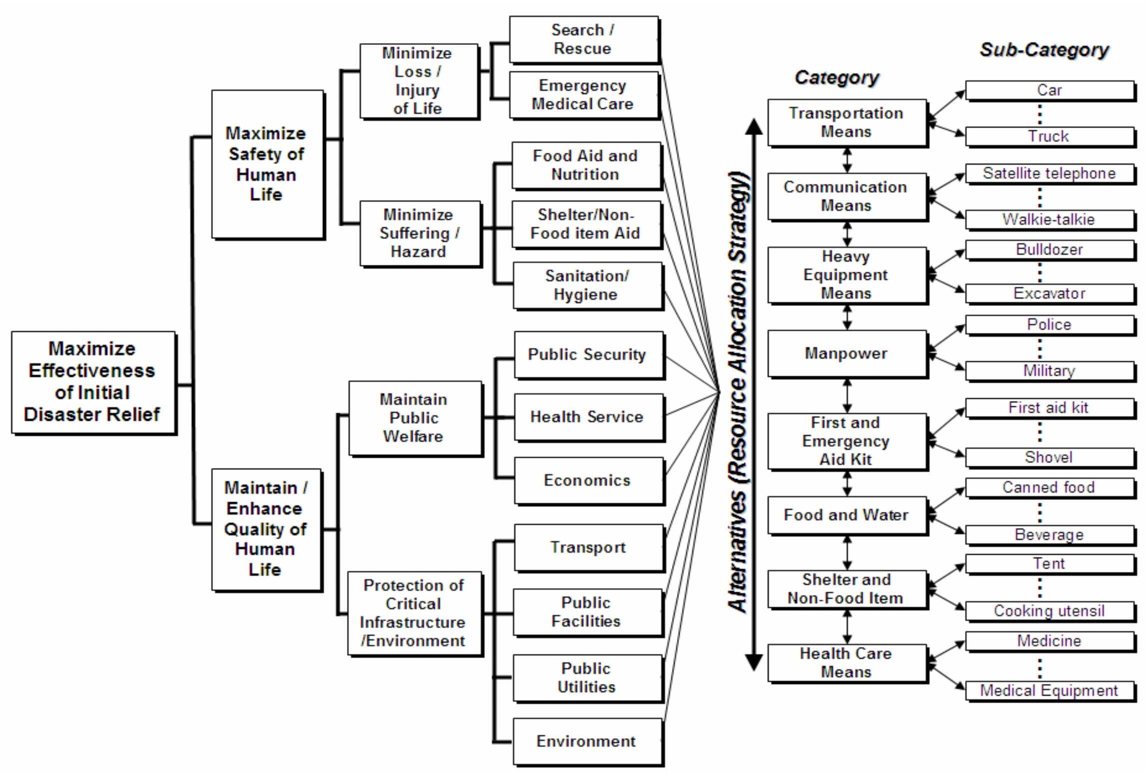


Figure 9. Value Hierarchy with Resource Allocation Strategy

For this research, alternatives are resources allocation strategies consisting of various means objectives for disaster relief operations. Each means objective includes various kinds of resources as sub-categories as shown in Figure 9. Table 8 shows these resources in more detail. Each resource may or may not be required for accomplishing particular objectives. For instance, *transportation means* resources are needed for nearly all relief operations, while *food and water* resources may only be needed at a feeding operation. Alternatives composed of detailed allocation strategies will be discussed later in the chapter.

Table 8. Relief Resources

Category	Resources (Relief Needs)
Transportation Means	planes, helicopters, boats, ships, lifeboats, cars, trucks
Communication Means	satellite telephones, walkie-talkies
Heavy Equipment Means	excavators, bulldozers, cranes,
Manpower	police, military arm, health care force, coast guard
First and Emergency Aid Kit	life jackets and buoys, stretches, first aid kits, sterilizing medicine, shovel, ropes, torch, saw,
Food and Water	instant food, dry food, bread, canned food, beverages
Shelter and Non-Food Item	tents, rain coats, mobile toilets, blankets, clothes, water storing tools, cooking utensils, fuel, sleeping mat
Health Care Means	medicine, vaccine, epidemical prevention medicine, medical equipment

Selecting a scale to measure attainment of a particular objective is not simple. There is no general system-wide basis for comparing the severity of different situations and prioritizing a set of resources accordingly. Gupta et al. (1998) suggest four steps to evaluate disaster (earthquake) mitigation strategies. First, risks are measured and mitigation goals are prioritized. Second, the effects of different mitigation strategies on separate components of disaster risk are assessed. Third, an indicator or scale that combines effects of mitigation strategies on various components of risk into a single measure is created. Finally, this value is translated into terms that are readily understandable such as dollar expenditures. In a similar manner, it may be suitable that the effectiveness of an alternative is estimated by a single measure and this value is translated into dollars.

When specifying evaluation measures, it is sometimes advantageous to select a simple evaluation measure scale rather than the more complex one used by specialists or researchers in a given field (Merrick et al. 2005). Simple evaluation measures, for example percentage (%), are easily understood by most people. For instance, percentage (%) of required response capability for the life saving mission will be increased if resources such as SAR teams, ambulances, helicopters, boats, etc. are made available. The need required in a particular area can be obtained through "damage and needs assessment" which is conducted with the goal of identifying needs in each disaster relief sector. After quantifying needs, the effectiveness of resources allocation strategies can be measured by determining what percentage of each need is met by the strategy. This value is translated into terms of dollars (demand costs). Table 9 is example of quantifying needs in the initial stage of disaster and Table 10 shows the evaluation measures of each objective and their definitions.

Table 9. Example of Quantifying Needs (Asian Disaster Preparedness Center 2000)

• Search and Rescue Teams per Missing People • Item (plastic sheeting or cooking sets) per Family • Shelter per Homeless People • Grams of Staple Food per Person for Days • Grams per Child per Day for Days (for supplementary feeding) • Liters per Person for days • Tons / Liters to Create Reserves

Table 10. Objectives / Evaluation Measures

Objectives	Evaluation Measures
Search / Rescue (SAR)	(%) response capability to meet life saving requirements
Emergency Medical Care	(%) response capability to meet first-aid requirements
Food Aid / Nutrition	(%) needed provision food and water to evacuee
Shelter / Non-Food Item Aid	(%) needed provision emergency housing / stock to evacuee
Sanitation / Hygiene	(%) needed provision of sanitary arrangement / stock to evacuee
Public Security	(%) response / prevention capability to various crime
Health Service	(%) response capability to meet medical requirements
Economics	(%) maintenance capability / availability of economical activities
Transport	(%) recovery / maintenance capability of public transportation
Public Facilities	(%) recovery / maintenance capability of public facilities
Public Utilities	(%) recovery / maintenance capability of public utilities
Environment	(%) recovery / maintenance capability of unpolluted inhabitant area

Next a SDVF must be created for each evaluation measure. However, there are no decision-makers from governments or organizations in this research, thus notional decision-makers' preferences and two value elicitation procedures presented by Kirkwood (1997) were used to create the notional SDVFs.

One of these procedures results in linear and piecewise-linear SDVFs requiring that the relative value increments be specified between each of the possible evaluation measure scores. For example, the value increments for the evaluation measure, *(%) needed provision food and water to evacuee,* between 0% and 50% and between 50% and 100% are equal as each additional piece of evaluation measure is a better for *Food Aid / Nutrition*. This assessment creates linearly increasing SDVF with equal value increments for each unit increase in the evaluation measure. (Merrick et al. 2005) The piecewise-linear SDVFs are elicited by identifying the least (or most) desirable outcome increment of the evaluation measure and then specifying the value of the remaining outcome increments relative to the least (or most) desirable one. For instance, to determine the SDVF over (%) *needed provision of sanitary arrangement / stock to evacuee* evaluation measure, suppose the value increments to be measured are going from 0% to 20%, 20% to 40%, 40% to 60%, 60% to 80%, and 80% to 100%. Further, moving from 80% to 100% is the least important jump, represented as v. Suppose going from 60% and 80% has the same value as going from 80% to 100% and going from 40% to 60% is twice as important as going from 80% to 100%. Finally going from 0% to 20% and from 20% to 40% is three times as important as from 80% to 100%. The total value of the measure must be 1 so the sum of all the value increment is $3v + 3v + 2v + v + v = 1$. Solving for v yields $v = 0.1$. Thus, the values are

$$v(0) = 0.0$$

$$v(20) = 0.0 + 3v = 0.0 + 3 \times 0.1 = 0.3$$

$$v(40) = 0.0 + 3v + 3v = 0.0 + 3 \times 0.1 + 3 \times 0.1 = 0.6$$

$$v(60) = 0.0 + 3v + 3v + 2v = 0.0 + 3 \times 0.1 + 3 \times 0.1 + 2 \times 0.1 = 0.8$$

$$v(80) = 0.0 + 3v + 3v + 2v + v = 0.0 + 3 \times 0.1 + 3 \times 0.1 + 2 \times 0.1 + 0.1 = 0.9$$

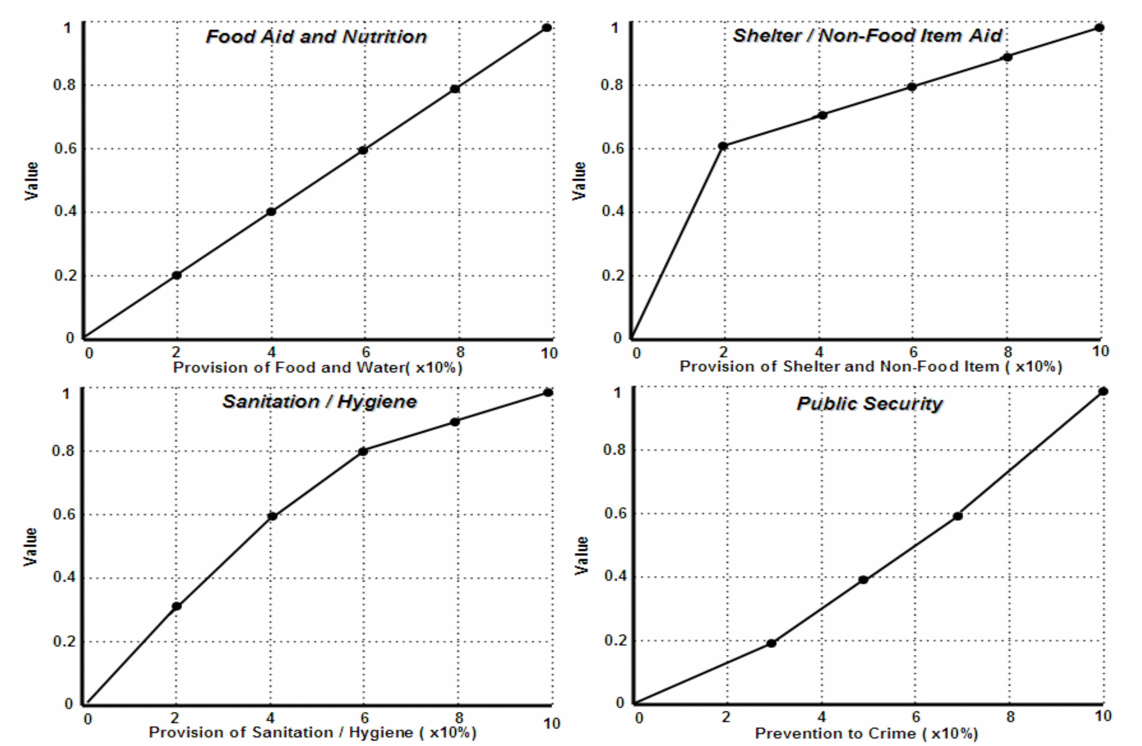
$$v(100) = 0.0 + 3v + 3v + 2v + v + v = 0.0 + 3 \times 0.1 + 3 \times 0.1 + 2 \times 0.1 + 0.1 + 0.1 = 1$$

The other procedure uses exponential SDVFs having a particular form which depends on the range of the evaluation measure and an exponential constant (ρ). If ρ is greater than zero, the SDVF is concave, and if ρ is less than zero, the SDVF is convex. When higher values of x are preferred to lower values, the exponential SDVF, $v(x)$, can be represented as: (Kirkwood 1997)

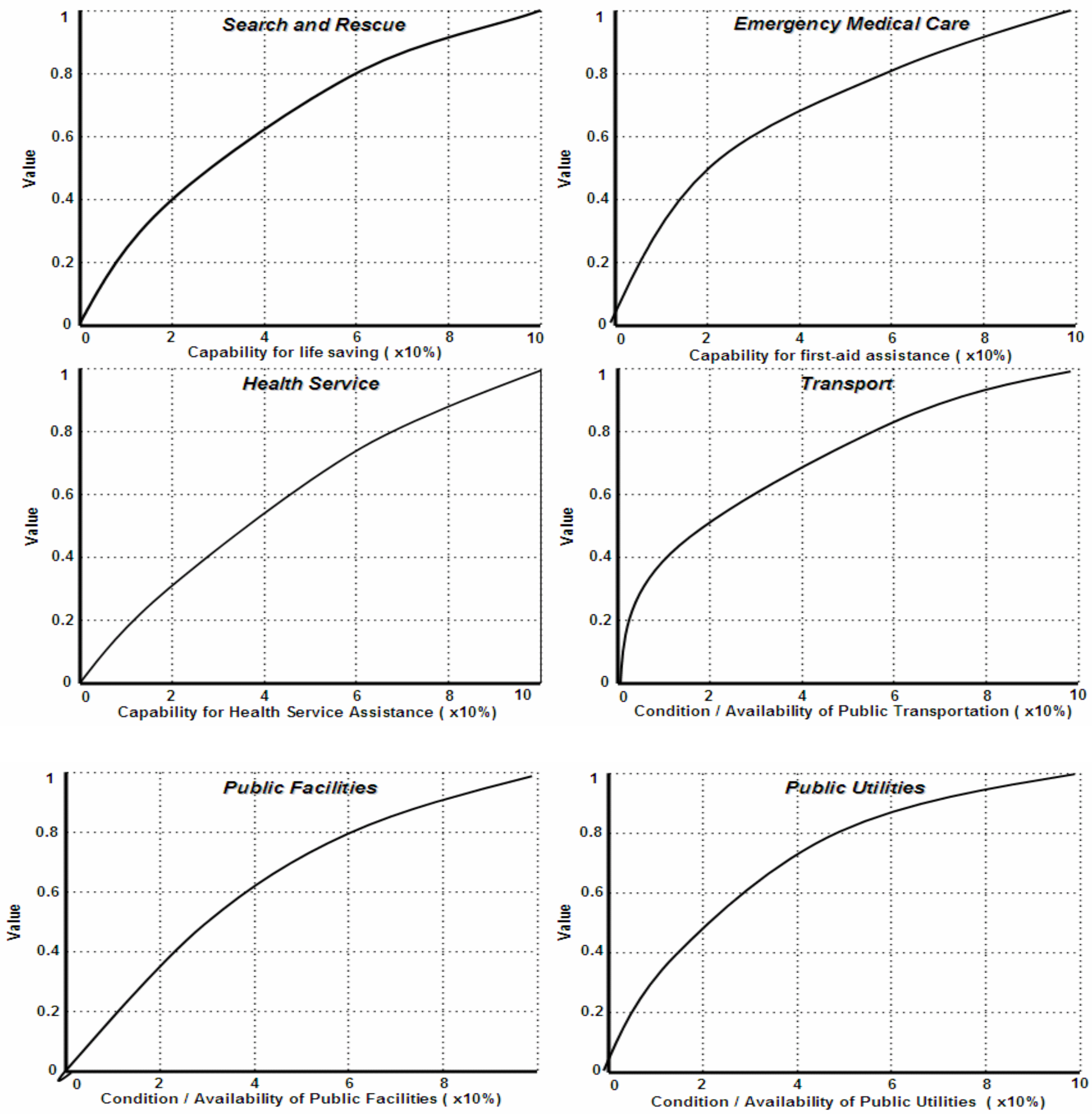
$$v(x) = \frac{1 - \exp[-(x - Low)/\rho]}{1 - \exp[-(High - Low)/\rho]}, \rho \neq Infinity, \rho \neq 0$$

$$v(x) = \frac{x - Low}{High - Low}, otherwise$$

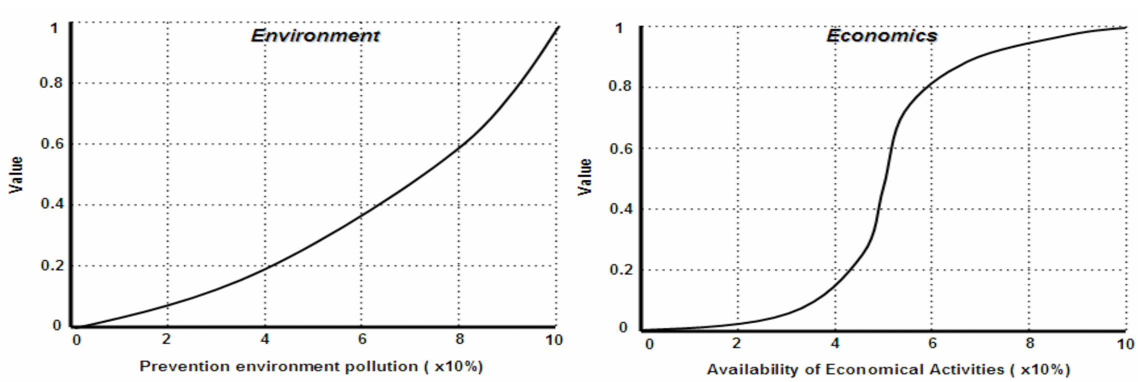
To find ρ the *midvalue*, or outcome with a value of .5, must be determined (Kirkwood 1997). For example, if for evaluation measure, (%) *response capability to meet first-aid requirements* an outcome of 20% is worth half of the value of the most preferred outcome 100%, then 20% is the midvalue. The value of ρ can be calculated using the normalized midvalue which found by subtracting the least preferred outcome and dividing by the range of outcomes (Kirkwood 1997). Once ρ is determined it is possible to use above equation to calculate the value for any outcome. The resulting SDVFs are shown in Figure 10.



(a) Linear and Piecewise Linear SDVF



(b) Exponential SDVF (Concave)



(c) Exponential SDVF (Convex) / S-Curve

Figure 10. SDVFs Developed by VFT Process

3.1.5 Weight Elicitation

The hierarchy must be weighed based on relative importance and variation (Merrick et al. 2005). For the purposes of this research, notional weights were applied on the hierarchy. Each objective was weighed through the swing-weighting process described by Kirkwood (1997). The swing-weighting procedure is as follows: 1) Rank the evaluation measures in the order of importance based on the swing in each measure from the worst score to the best score, 2) Determine the relative increase in value for each of the swings compared to either the smallest or largest swing, 3) Continue until all evaluation measures have been assessed, 4) Normalize the weights. For example, if decision-makers stated that the swing from the worst to best outcome for *Public Security* is 1.5 times as important as the swing over *Health Service*, and the swing over *Economics* is 1.25 times as important as the swing over *Public Security*, the normalized weights are 0.23, 0.35, 0.43 for *Health Service, Public Security*, and *Economics*, respectively.

Before determining weights, the purpose of this research - the development of a suitable resource allocating model for the initial three days - should be examined. Damage assessments are made at three damage degree categories: *High* (Red), *Medium* (Yellow), and *Low* (Green). Because the decision-makers preferences may change based on the severity and extent of a disaster's negative impacts on the community, each evaluation measure within the hierarchy must to be weighed for each of the different damage degrees. It is assumed that under the *Low* (green) damage degree, the resource allocation models do not add any significant contribution for disaster relief planning. Governments and individuals in low damaged areas have the capacity to procure resources for recovery without difficulties. Thus, only *High* (red) and *Medium* (yellow) damage degrees were considered as specific environments for eliciting weights.

Table 11. Damage Degrees (adapted FEMA 2004)

Damage Degree	Description
High (Red): ► ***Not Functional, Not Repairable***	This category would indicate that the infrastructure item cannot be used and will require extensive repair (months) or replacement prior to future use.
Medium (Yellow): ► ***Not Functional, But Repairable***	This category would indicate that the infrastructure item cannot be used at this time but will be usable within a short period of time (days) after restoration or repair to its original condition
Low (Green): ► ***Functional with Light Damage***	The infrastructure item can still be used for its intended purpose, however, some minor repairs must be accomplished to restore it to full service or original use

Figure 11 shows notional weights for disaster relief value hierarchies for the *High* (a) and *Medium* (b) damage degrees. In most situations if the damage degree was estimated as *High*, relief efforts in the first three days should be focused on the saving of lives through *Search and Rescue* and *Emergency Medical Care* activities. Thus in the first tier of the High Damage Degree hierarchy (presented in Figure 11(a)),*"Maximize Safety of Human Life"* has a weight of .675 while *"Maintain / Enhance Quality of Human Life"* has a weight of .325. On the other hand, in the first tier of Figure 11-(b), *"Maximize Safety of Human Life"* and *"Maintain / Enhance Quality of Human Life"* were weighted equally at 0.5. For both hierarchies, all other sub-components were weighted equally within their tiers.

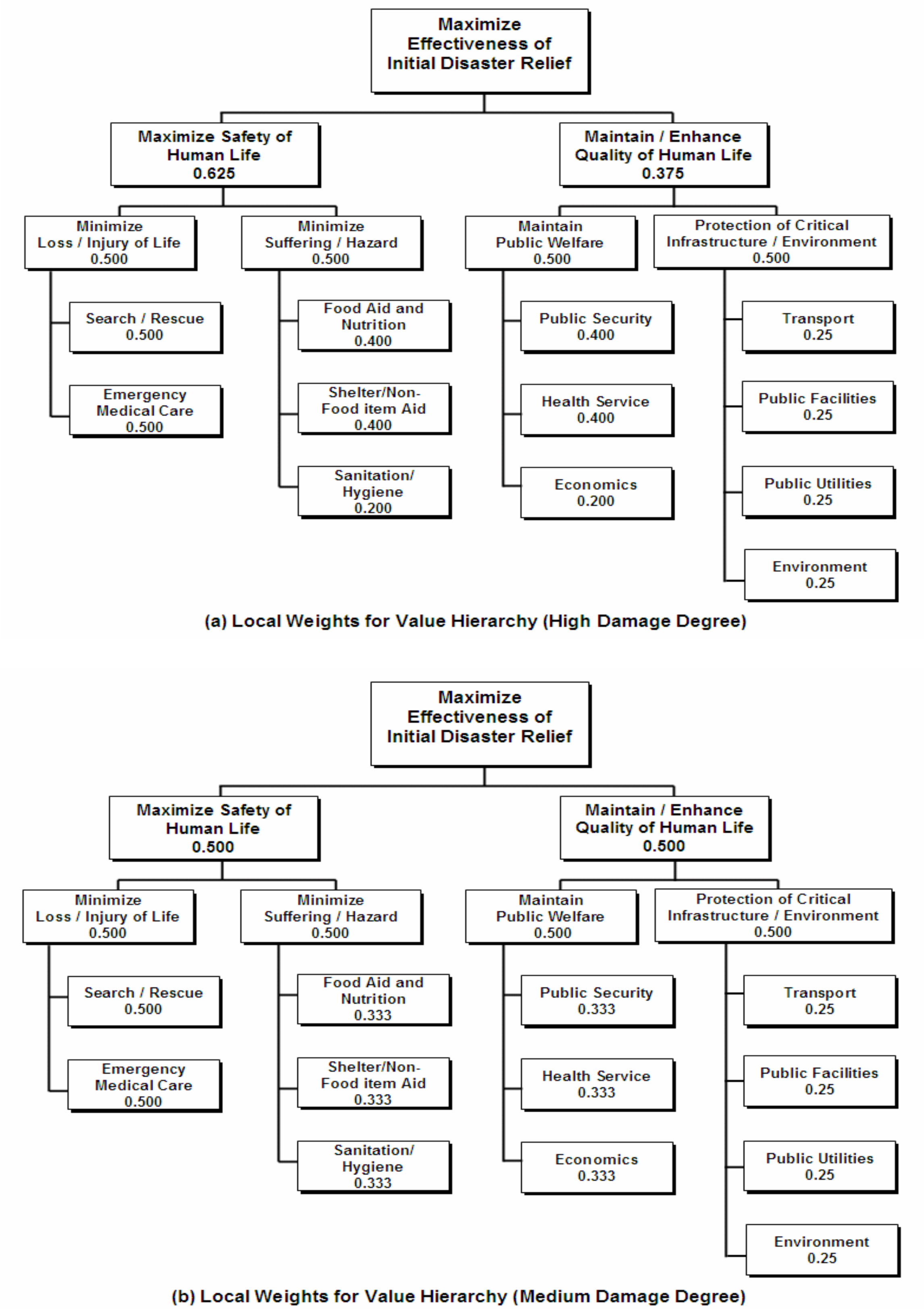


Figure 11. Notional Weights for Initial Disaster Relief Value Hierarchy

In Figure 11 are local weights (i.e. each weight is relative to the others on the same tier). Global weights are needed for the attributes to use the hierarchy to score alternatives. The global weights for an attribute can be calculated by multiplying the local weights down the branch to the attribute. For example, in the Medium Damage Degree case the global weight for *Public Security* is 0.5 * 0.5 * 0.333 = 0.083.

3.2 Mathematical Approach for Solving the Value Model

In the previous section, a value model was developed using the VFT process and critical considerations, objectives, and resources allocation strategies as alternatives in the initial disaster recovery phase were presented. This section describes a MP approach to provide optimal allocation of the resources presented in Table 8 to maximize the decision-maker(s) value in the initial disaster relief efforts.

As described earlier, the level of attainment for each objective is measured as a percentage of need based on the initial damage assessment. These percentages are scored using single dimensional value functions (SDVFs). The overall value score for the alternatives can be calculated through additive value function (Kirkwood 1997). However, for resource allocation problems the number of alternatives (different allocations) is very large and it is infeasible to score each alternative. In this case, a MP model is used to explore the extreme points of the solution space to find the optimal resource allocation in terms of the value hierarchy. To accomplish this, the SDVFs must be modeled mathematically. If the SDVF is linear, this is relatively easy. However, it is common in complex decision problems for the SDVFs to be non-linear (typically exponential or S-shaped). In the latter case it is beneficial to model the non-linear

SDVFs with a linear approximation so that existing linear programming software or techniques can be used.

3.2.1 Linear Single Dimensional Value Functions

For Linear Single Dimensional Value Functions (L-SDVFs), each incremental change in input provides the same increase in value. The slope (or value per unit change) can be calculated by examining the vertical to horizontal axis ratio. The sign can be positive (increasing) or negative (decreasing). For example, if every unit increase in*" percentage of food and water provision"* provides the same increase in value, the SDVF for *"Food Aid and Nutrition"* would increase linearly with a slope of 0.01. This is presented in Figure 12. The L-SDVF is modeled in the MP by using an objective function coefficient equal to the slope of the L-SDVF.

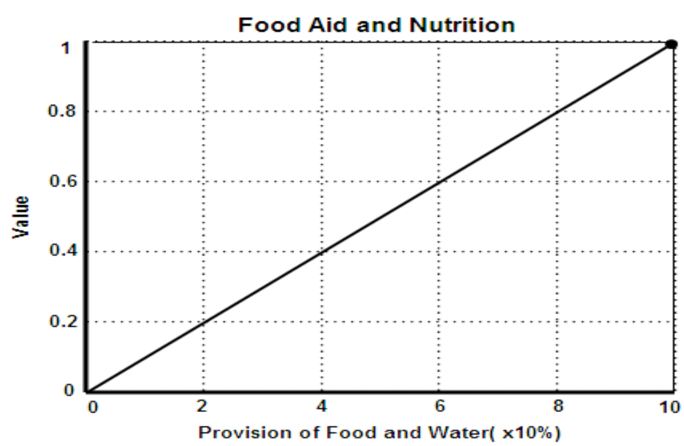


Figure 12. Example of L-SDVF

3.2.2 Piecewise Linear Single Dimensional Value Functions

The procedure for determining a Piecewise Linear Single Dimensional Value Function (PWL-SDVF) is demonstrated in Kirkwood (1997). The relative value increments between discrete points in the evaluation measure are determined and used to describe the value function. The mathematical formulation of PWL-SDVF is more cumbersome than that of the L-SDVF. The evaluation measure is represented by *r* segments along the measure axis based on dividing points: $d_1, d_2, \ldots, d_r$ and *r* points along the value axis c_1, c_2,..., c_r. Figure 13 presents an example case in which r = 3. In PWL-SDVFs, each linear segment must be represented with a separate decision variable. The slope of each segment is used as the objective function coefficient for the corresponding segment decision variable. Notional examples of PWL-SDVFs for *Sanitation / Hygiene* and *Public Security* are shown in Figure 14. For PWL-SDVFs, it may be necessary to include additional constraints in the MP formulation to ensure the segment decision variables are assigned a positive value in the correct order and that each segment is utilized in its entirety before the next segment decision variable is assigned. The form for these constraints and the circumstances under which they must be included are covered in the next section.

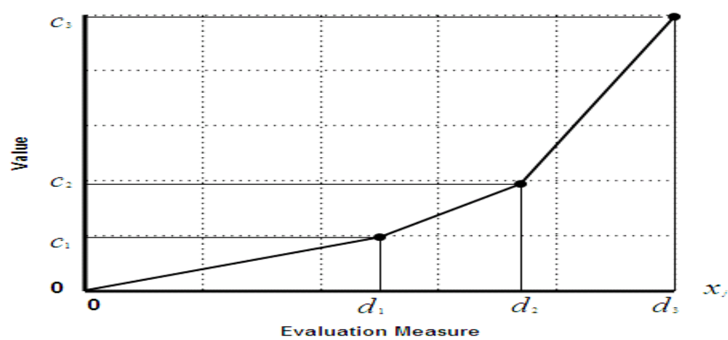


Figure 13. PWL-SDVF

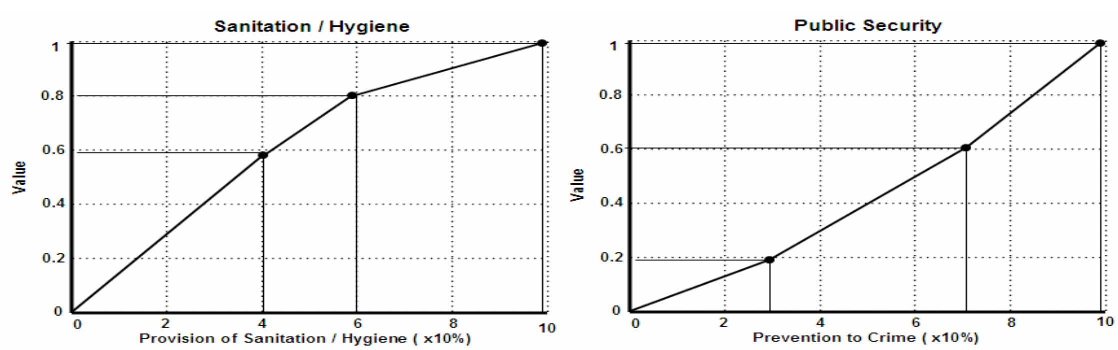


Figure 14. Example of PWL-SDVF

3.2.3 Piecewise Linear Approximation for Non-Linear SDVFs

Some SDVFs take a non-linear form; exponential SDVFs are common. Kirkwood (1997) provides equations for increasing and decreasing scaled exponential SDVFs. However, occasionally an SDVF has a more complex shape, such as an S-curve. In either case, solving a non-linear MP is more difficult and only guarantees global optimality under specific circumstances. Therefore, a piecewise linear approximation is used in this research to model non-linear SDVFs.

A piecewise linear approximation of a non-linear SDVF is modeled mathematically in the same manner as PWL-SDVFs. The distinction is made in how the decision-maker(s) preferences are assessed and modeled. For PWL-SDVFs, the value increments of the segments are assessed through the decision-maker(s) and modeled as a PWL-SDVF. For non-linear SDVFs, the non-linear function is assessed through the decision-maker(s). This type of assessment typically requires fewer comparisons than the PWL-SDVF. The analyst then selects the points along the evaluation measure axis at which to segment the non-linear function. The piecewise linear approximations for three common non-linear functions are presented in the next 3 subsections.

(1) Convex Piecewise Linear Approximation

In Figure 15, the evaluation measure, *Environment*, is represented by the x_j axis and divided into three points which correspond to three values on the value axis creating a three segment approximation. Using Figure 15 as an example, the following steps show how to mathematically model a piecewise linear approximation for a nonlinear convex value function. (Jensen and Bard 2003)

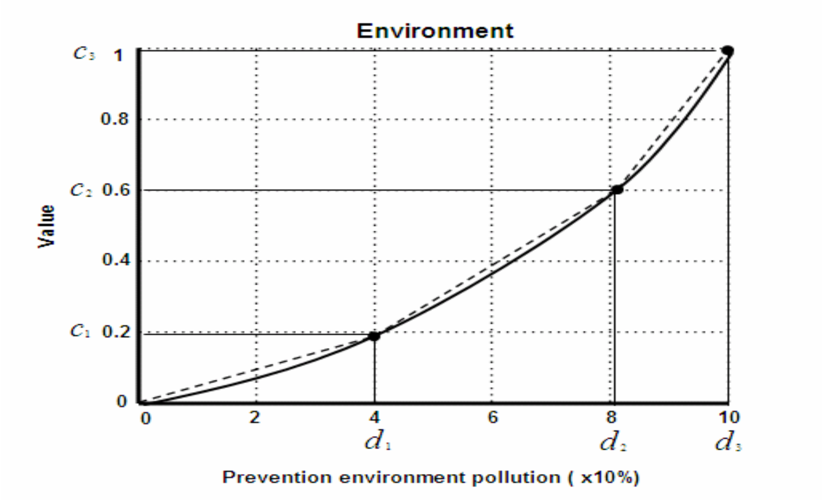


Figure 15. Example of Convex Piecewise linear Approximation

• *Define Variables for the Segments*: First, select the values of the breakpoints for evaluation measure (d_1 = 4, d_2 = 8, d_3 = 10) and compute the corresponding value for each point ($c_1 = 0.2$, $c_2 = 0.6$, $c_3 = 1$).

• *Compute the Slope of Each Segment*: (E: Environment)

$$s_{jk} = (c_k - c_{k-1})/(d_k - d_{k-1}) \longrightarrow s_{E1} = 0.05,\ s_{E2} = 0.1,\ s_{E3} = 0.2$$

• *Replace the terms with Linear Approximation*:

$$f_j(x_j) = \sum_{k=1}^{r_j} s_{jk} x_{jk} \longrightarrow v_E(x_E) = \sum_{k=1}^{3} s_{Ek} x_{Ek} = 0.05 x_{E1} + 0.1 x_{E2} + 0.2 x_{E3}$$

• *Add the Linking Constraint Relating New Variables to Old*: $x_E = \sum_{k=1}^{3} x_{Ek}$

• *Define the Binary Variables:*

y_{jk} = 1 (if piece k is included) or 0 (not included), for k = 2, 3

• *Add the Bound Constraints:*

$$d_1 y_{j2} \le x_{j1} \le d_1, \longrightarrow 4 y_{E2} \le x_{E1} \le 4$$

$$(d_k - d_{k-1}) y_{j,k+1} \le x_{jk} \le (d_k - d_{k-1}) y_{jk},\ \ k{=}2 \longrightarrow 4 y_{E3} \le x_{E2} \le 4 y_{E2}$$

$$0 \le x_{jr_j} \le (d_{r_j} - d_{r_j - 1}) y_{jr_j} \quad \rightarrow \quad 0 \le x_{E3} \le 2 y_{E3}$$

The binary variables and the bound constraints ensure each preceding segment is fully used prior to using the next segment. For example, x_{E2} cannot be > 0 if $x_{E1} < 4$. However, when a convex piecewise linear value function is used and the problem is one of minimization, it is not necessary to introduce the binary variables. In this case, the bound constraints reduce to, $0 \le x_{Ek} \le d_k - d_{k-1}$, $k = 1, 2, 3$ (Jensen and Bard 2003).

(2) Concave Piecewise Linear Approximation

Concave piecewise linear approximation is accomplished in a similar manner. In Figure 16, the evaluation measure, *Search and Rescue*, is represented by the x_j axis and divided into three points which correspond to three values on the value axis creating a three segment approximation. Using Figure 16 as an example, the following steps demonstrate how to mathematically model a piecewise linear approximation for a nonlinear concave value function. (Jensen and Bard 2003)

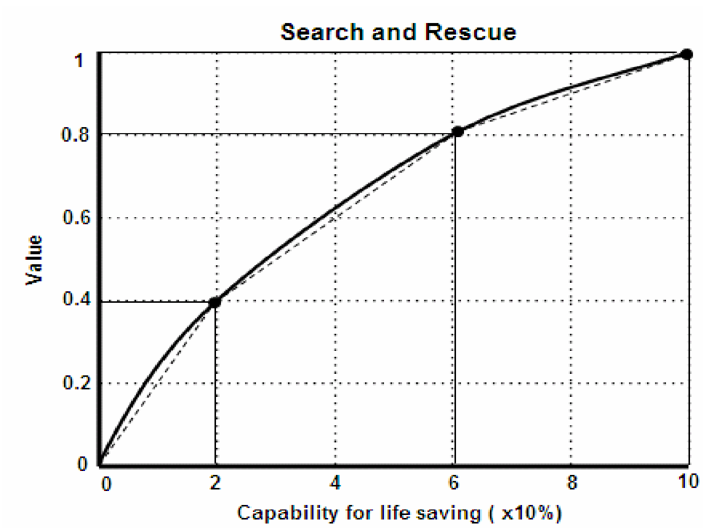


Figure 16. Example of Concave Piecewise linear Approximation

• *Define Variables for the Segments*:

$d_1 = 2.0,\ d_2 = 6.0,\ d_3 = 10.0 \quad \longrightarrow \quad c_1 = 0.4,\ c_2 = 0.8,\ c_3 = 1$

• *Compute the Slope of Each Segment*:

$s_{jk} = (c_k - c_{k-1})/(d_k - d_{k-1}) \quad \longrightarrow \quad s_{Life,1} = 0.2,\ s_{Life,2} = 0.1,\ s_{Life,3} = 0.05$

• *Replace the terms with Linear Approximation*:

$$f_j(x_j) = \sum_{k=1}^{r_j} s_{jk} x_{jk} \longrightarrow v_{Env}(x_{Env}) = \sum_{k=1}^{3} s_{Life,k} x_{Life,k} = 0.2x_{Life,1} + 0.1x_{Life,2} + 0.05x_{Life,3}$$

• *Add the Linking Constraint Relating New Variables to Old*: $x_j = \sum_{k=1}^{3} x_{Life,k}$

• *Add the Bound Constraints*: $0 \le x_{Life,1} \le 2$, $0 \le x_{Life,2} \le 4$, $0 \le x_{Life,3} \le 4$

When a concave piecewise linear value function is used and the problem is one of maximization, it is not necessary to introduce the binary variables.

(3) S-Curve Piecewise Linear Approximation

Some SDVFs have an *S-curve* shape (Figure 17). In this case, the SDVF can be divided into two parts, convex and concave, and the same steps shown in the above sections can be used to obtain piecewise linear approximations of the convex and concave sections. However, the binary variables must be introduced for both the convex and concave parts regardless of whether the problem is one of minimization or maximization.

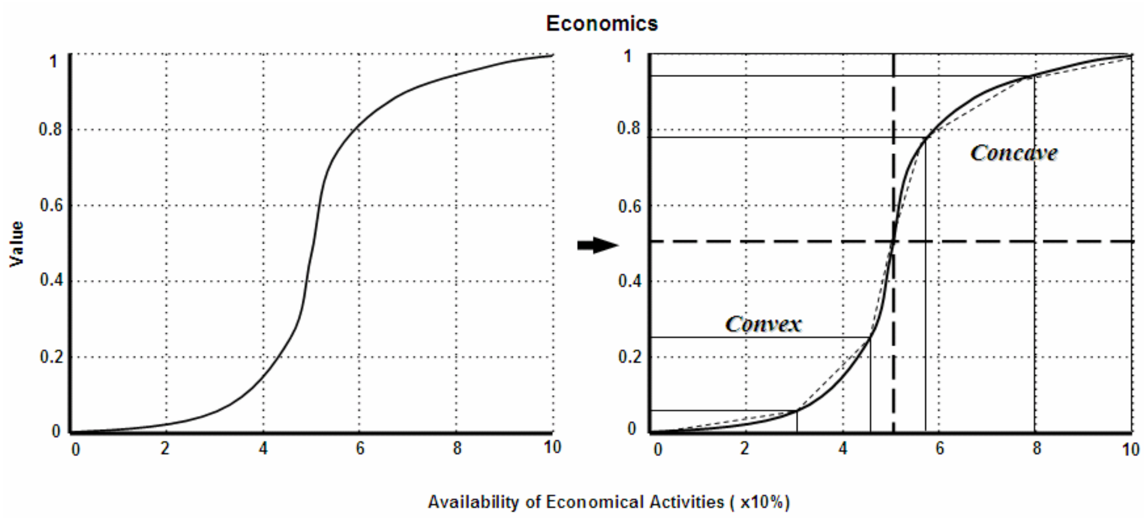


Figure 17. Example of *S-Curve* Piecewise linear Approximation

3.2.4 Mixed Integer Linear Programming Approach

In this section, mixed integer linear programming (MILP) model is introduced to solve the resource allocation value model. A MILP is a mathematical programming model with a linear objective function and linear constraints in which some of the variables are required to take on integer values. (Linderoth 2004) The additive value function which reflects the decision-maker(s) values provides the objective function. Although the resource allocation decision variables are treated as continuous, the piecewise linear approximations of evaluation measures introduced binary integer variables transforming the MP to a MILP. In addition to the constraints required by the piecewise linear approximations, the allocation of resources is restricted by budgetary constraints.

To allow the resource allocation problem to be modeled under budgetary restrictions, all of the SDVFs are converted to a capital scale. For example, if $59,000 were needed to purchase 100% of the *Food Aid and Nutrition* resources, the horizontal axis on the measure scale would go from $0 on the left to $59,000 on the right with

$v(59000) = 1$. For the budgetary constraints, let a_{ij} equal the capital *needed* (based on the initial damage assessment) to purchase the required resources of category i for attribute j. Let D_j equal the total capital *needed* to purchase all the required resources for attribute j. It is assumed that enough of each resource is available given that capital is available. Each attribute j is represented with a single decision variable, x_j, specifying the total capital *allocated* to purchase the required resources for that attribute. Table 12 presents the resource requirements in variable form.

Table 12. Example of Resources Cost Combination with Attributes

Resource (i)	Resource usage (\$) per attribute j					Resource Available (\$)
	1	2	. . . .	11	12	
#1 Transportation Means	$a_{1,1}$	$a_{1,2}$	. . . .	$a_{1,11}$	$a_{1,12}$	
#2 Communication Means	$a_{2,1}$	$a_{2,2}$	. . . .	$a_{2,11}$	$a_{2,12}$	
#3 Heavy Equipment Means	$a_{3,1}$	$a_{3,2}$	. . . .	$a_{3,11}$	$a_{3,12}$	
#4 Manpower	$a_{4,1}$	$a_{4,2}$	. . . .	$a_{4,11}$	$a_{4,12}$	
#5 First / Emergency Aid Kit	$a_{5,1}$	$a_{5,2}$	. . . .	$a_{5,11}$	$a_{5,12}$	Budget
#6 Food and Water	$a_{6,1}$	$a_{6,2}$	. . . .	$a_{6,11}$	$a_{6,12}$	
#7 Shelter / Non-Food Item	$a_{7,1}$	$a_{7,2}$	. . . .	$a_{7,11}$	$a_{7,12}$	
#8 Health Care Means	$a_{8,1}$	$a_{8,2}$	. . . .	$a_{8,11}$	$a_{8,12}$	
Demand	D_1	D_2	. . . .	D_{11}	D_{12}	Total

The mathematical programming formulation is:

- *Maximize* $Z = \sum_{j=1}^{12} w_j v(x_j)$ *: overall value of evaluation measures*

    • *Replace objective function terms with*

    1) Case of L-SDVF: $v(x_j) = cx$, *c=slope*

2) Case of PWL-SDVF:

$v(x_j) = \sum_{k=1}^{r_j} s_{jk} x_{jk}$ *, where r =number of segments and s_{jk} is the slope of the k^{th} segment*

- *Subject to*:

$$\sum_{j=1}^{12} x_j \leq Total\ Available\ Budget$$

Upper bound on allocation variables: *0≤ $x_j \leq D_j$*

1) Case of convex PWL-SDVF:

• *add the linking constraint relating new variables to old*

$$x_j = \sum_{k=1}^{r_j} x_{jk}$$

• *define the binary variables and add the bound constraints*

$y_{jk} = 1$ (*if segment k is included) or 0 (not included),*

$$d_1 y_{j2} \leq x_{j1} \leq d_1,$$

$$(d_k - d_{k-1}) y_{j,k+1} \leq x_{jk} \leq (d_k - d_{k-1}) y_{jk},\ k = 2,\dots,r_j - 1$$

$$0 \leq x_{jr_j} \leq (d_{r_j} - d_{r_j - 1}) y_{jr_j}$$

2) Case of concave PWL-SDVF:

• *add the linking constraint relating new variables to old*

$$x_j = \sum_{k=1}^{r_j} x_{jk}$$

• *add the bound constraints*

$$0 \leq x_{Ek} \leq d_k - d_{k-1}$$

The objective function measures the overall value produced by a given allocation. The global weight, w_j, is calculated as shown in section 3.1.5. The budget constraint restricts that the total resources consumed not exceed the available budget. The model will find an optimal funding of attributes that maximizes the value as defined in the value function.

3.3 Summary

This chapter began with the development of the value model for resource allocation for the initial disaster relief operations. The VFT approach was used to generate multiple fundamental objectives and model the decision-maker(s) preferences. A MILP model was purposed to find the optimal resource allocation to maximize the decision-maker(s) values. In the next chapter, the methods are applied to a notional scenario.

4. Results and Analysis

In this chapter, the value hierarchy and mathematical programming model described in the previous chapter are use to determine the resource allocation for the initial disaster relief operations of a notional scenario. The resource allocations for several budget scenarios are compared for both high and medium damage degrees.

4.1 Hurricane Scenario Model Formulation

4.1.1 Description of Scenario

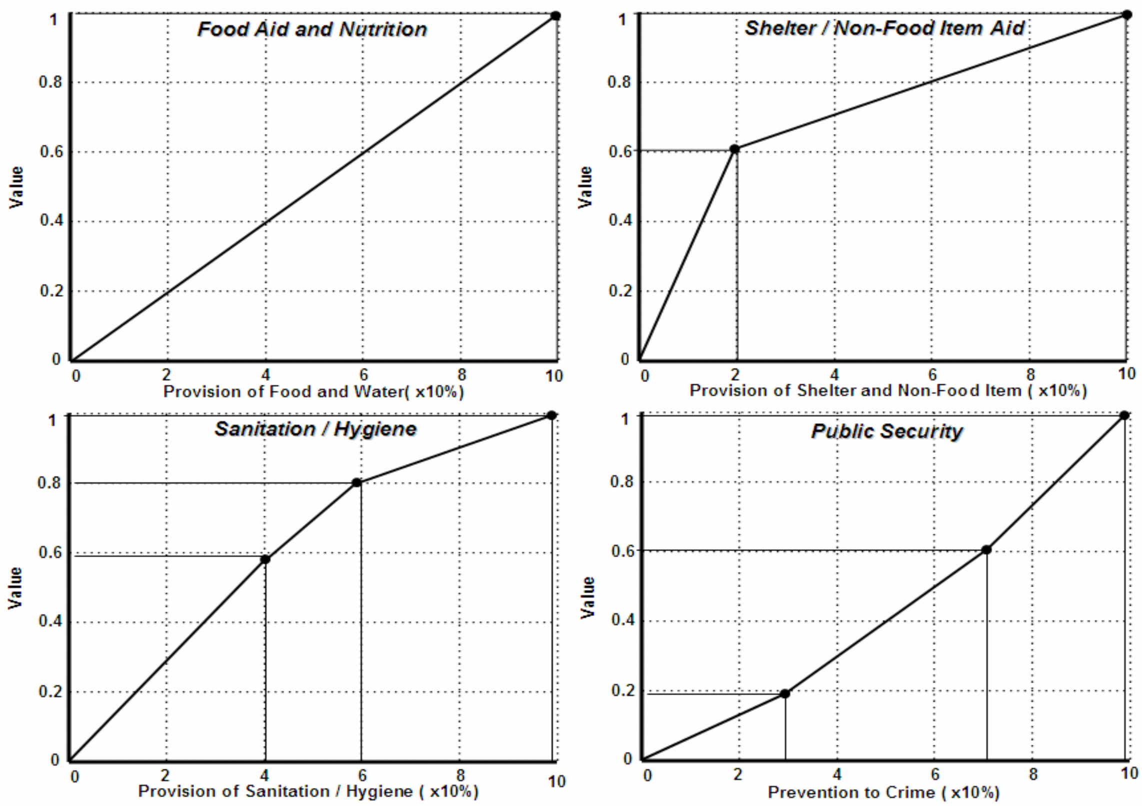
A hurricane and flash flood event has occurred impacting the safety and quality of life and infrastructure in a community. Disaster relief experts have performed the initial damage assessment identifying the severity and extent of the disasters' impact on human life, the economy and the environment in the community and determined what resources are needed to address each sector.

Fortunately the disaster relief organization was prepared and, along with community leaders, had previously developed a value hierarchy for both high and medium damage scenarios (shown in Table 13 and Figure 18). With the initial damage assessment in hand, they are now prepared to use the value hierarchy and the MP model to evaluate the impact of varying levels of funding and determine the resource allocation for each level.

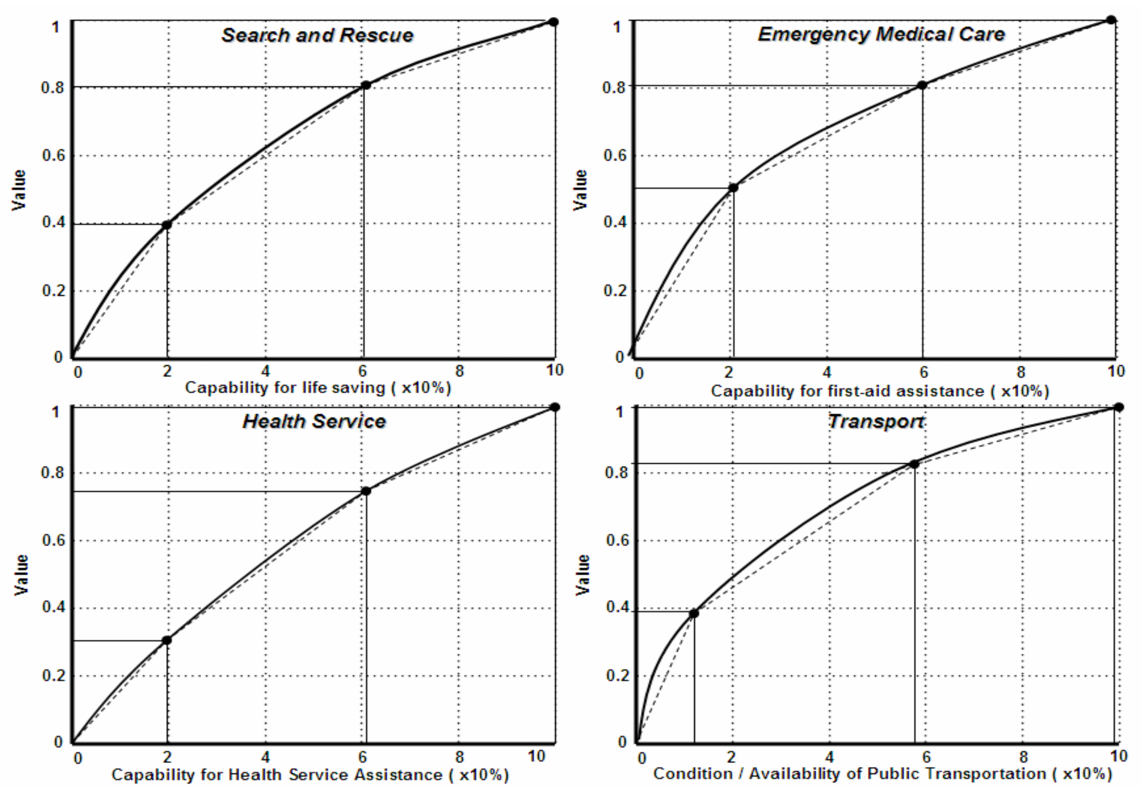
Table 13. The Result of VFT Analysis

Objectives			Descriptions	Global Weight
Maximize Safety of Human Life ***(0.625/0.5)***	Minimize Loss / Injury of Life ***(0.5/0.5)***	Search / Rescue ***(0.5/0.5)***	Maximize number of people in imminent danger who are rescued	***0.156/ 0.125***
		Emergency Medical Care ***(0.5/0.5)***	Minimize mortality of victims	***0.156/ 0.125***
	Minimize Suffering / Hazard ***(0.5/0.5)***	Food Aid and Nutrition ***(0.4/0.333)***	Maximize provision of food / water to evacuees	***0.125/ 0.083***
		Shelter/Non-Food item Aid ***(0.4/0.333)***	Maximize provision of emergency housing for evacuees	***0.125/ 0.083***
		Sanitation/ Hygiene ***(0.2/0.333)***	Maximize provision of sanitary arrangements for evacuees	***0.063/ 0.083***
Maintain / Enhance Quality of Human Life ***(0.375/0.5)***	Maintain Public Welfare ***(0.5/0.5)***	Public Security ***(0.4/0.333)***	Maximize prevention of crime / chaos	***0.075/ 0.083***
		Health Service ***(0.4/0.333)***	Maximize responses to health care requirements	***0.075/ 0.083***
		Economics ***(0.2/0.333)***	Maximize resident satisfaction with public economical activities in affected area	***0.038/ 0.083***
	Protection of Critical Infra-structure / Environ-ment ***(0.5/0.5)***	Transport ***(0.25/0.25)***	Minimize further damage and maximize repair of roads, bridges, subway and related infrastructure in affected area	***0.047/ 0.063***
		Public Facilities ***(0.25/0.25)***	Minimize further damage and maximize repair of school, downtown, harbor, port, air port, stormwater system, power plant, etc. in affected area	***0.047/ 0.063***
		Public Utilities ***(0.25/0.25)***	Minimize further damage and maximize repair of power and phone lines, water treatment plant utilities in affected area	***0.047/ 0.063***
		Environment ***(0.25/0.25)***	Maximize prevention of environment damage	***0.047/ 0.063***

(High damage degree / Medium damage degree)



(a) Linear and Piecewise Linear SDVF



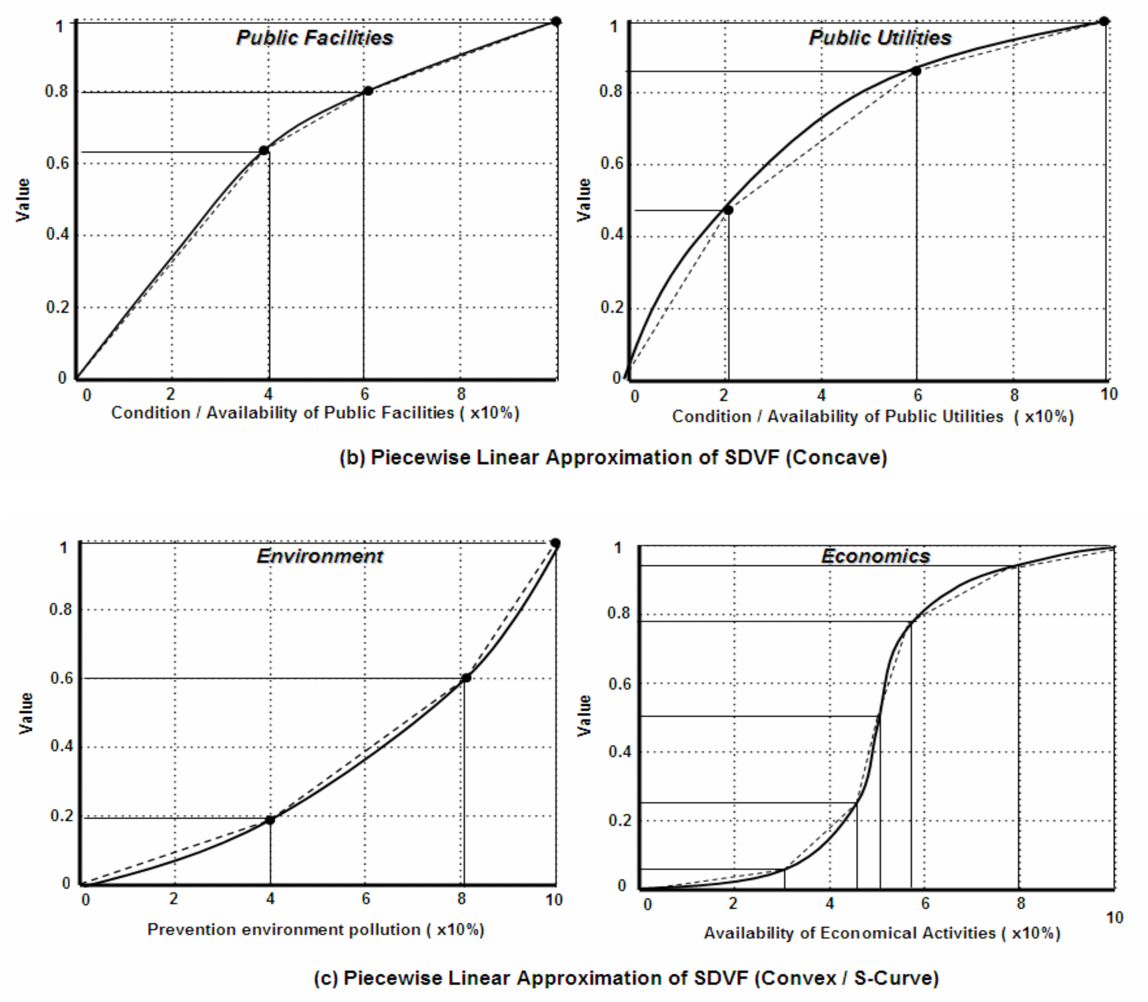


Figure 18. Attribute Single Dimensional Value Functions

4.1.2 Mixed Integer Linear Programming Formulation

With the data determined, the Mixed Integer Linear Program (MILP) model can be used to determine the optimal value and resource allocation for each budget scenario. The three budget scenarios used in this example are presented in Table 14. This information can be used to request funding and to efficiently allocate funding once received. First, the initial damage estimate is used to determine the capital required in each resource category for each attribute. This data is presented in Table 15. Second, all evaluation measures are translated into dollar expenditures. These results are presented in Table 16. Finally, the data in the model is specified using the translated SDVFs.

Table 14. Different Budget Scenario for High / Medium Damage Degree

	Budget Scenario		
	B_1 (Low)	B_2 (Medium)	B_3 (High)
Budget Amount (×1000 $)	450	480	510

Table 15. Notional Resource cost–Attribute Combinations Data

Resource (i)	Resource usage ($) per unit of attribute												Available Budget
	The lowest objectives (attribute: j)												
	1	2	3	4	5	6	7	8	9	10	11	12	
#1	16.8	15.8	10.5	9.1	8.2	10.1	9.2	9	14.9	15.1	14.5	13.9	(×1000 $)
#2	10.6	9.8	7.5	6.8	5.6	9.1	7.0	7.2	9.9	8.5	8.7	8.6	
#3	16.7	15.3	7.3	13.5	5.1	11.9	9.9	11.5	21.7	22.1	20.9	21.5	
#4	16.2	15.1	11.5	12.6	9.1	15.2	13.6	11.4	12.8	12.9	12.8	12.7	
#5	6.8	10.5	-	-	-	-	9.9	-	-	-	-	-	
#6	-	-	20	-	-	-	-	-	-	-	-	-	
#7	-	2.9	2.9	16	3	-	-	-	-	-	-	-	
#8	-	7.8	-	-	10.5	-	19.5	-	-	-	-	-	
Demand	67.1	77.2	59.7	58	41.5	46.3	69.1	39.1	59.3	58.6	56.9	56.7	**689.5** / $\boldsymbol{B}_{1,2,3}$

Resource (i)		Attribute (j)	
#1. Transportation Means #2. Communication Means #3. Heavy Equipment Means #4. Manpower	#5. First / Emergency Aid Kit #6. Food and Water #7. Shelter and Non-Food Item #8. Health Care Means	1. Search / Rescue 2. Emergency Medical Care 3. Food Aid / Nutrition 4. Shelter / Non-Food item Aid 5. Sanitation / Hygiene	6. Public Security 7. Health Service 8. Economics 9. Transport 10. Public Facilities 11. Public Utilities 12. Environment

Table 16. Evaluation Measures Translated *Dollar ($)* Expenditures

Objectives	Description	Evaluation Measures	
		Percentage (%)	*Dollar* ($\times 1000\$$)
Search / Rescue	Response capability for life saving	0 — 100	0 — 67.1
Emergency Medical Care	Response capability for first-aid	0 — 100	0 — 77.2
Food Aid / Nutrition	Provision food and water to evacuee	0 — 100	0 — 59.7
Shelter / Non-Food Item Aid	Provision emergency housing / stock to evacuee	0 — 100	0 — 58.0
Sanitation /Hygiene	Provision sanitary arrangement / stock to evacuee	0 — 100	0 — 41.5
Public Security	Response / prevention capability to various crime	0 — 100	0 — 46.3
Health Service	Response capability for medical requirements	0 — 100	0 — 69.1
Economics	Maintenance capability / availability of economical activities	0 — 100	0 — 39.1
Transport	Recovery / maintenance capability of public transportation	0 — 100	0 — 59.3
Public Facilities	Recovery / maintenance capability of public facilities	0 — 100	0 — 58.6
Public Utilities	Recovery / maintenance capability of public Utilities	0 — 100	0 — 56.9
Environment	Recovery / maintenance capability of unpolluted inhabitant area	0 — 100	0 — 56.7

The MILP formulation is as follows:

• *Objective Function: Maximize* $Z = \sum_{j=1}^{12} w_j v(x_j)$

1) The case of high damage degree:

$$Z = 0.156\,v(x_1) + 0.156\,v(x_2) + 0.125\,v(x_3) + 0.125\,v(x_4) + 0.063\,v(x_5) + 0.075\,v(x_6)$$
$$+ 0.075\,v(x_7) + 0.038\,v(x_8) + 0.047\,v(x_9) + 0.047\,v(x_{10}) + 0.047\,v(x_{11}) + 0.047\,v(x_{12})$$

2) The case of medium damage degree:

$$Z = 0.125\,v(x_1) + 0.125\,v(x_2) + 0.083\,v(x_3) + 0.083\,v(x_4) + 0.083\,v(x_5) + 0.083\,v(x_6)$$
$$+ 0.083\,v(x_7) + 0.083\,v(x_8) + 0.063\,v(x_9) + 0.063\,v(x_{10}) + 0.063\,v(x_{11}) + 0.063\,v(x_{12})$$

3) *Replace the terms with Linear Approximation:* $v(x_j) = \sum_{k=1}^{r_j} s_{jk} x_{jk}$,

where, r =number of segments and s_{jk} *is the slope of the* k^{th} *segment*

$$v(x_1) = 0.03x_{11} + 0.015x_{12} + 0.007x_{13}$$

$$v(x_2) = 0.032x_{21} + 0.010x_{22} + 0.006x_{23}$$

$$v(x_3) = 0.017x_3$$

$$v(x_4) = 0.052x_{41} + 0.009x_{42}$$

$$v(x_5) = 0.036x_{51} + 0.024x_{52} + 0.012x_{53}$$

$$v(x_6) = 0.014x_{61} + 0.022x_{62} + 0.029x_{63}$$

$$v(x_7) = 0.022x_{71} + 0.016x_{72} + 0.009x_{73}$$

$$v(x_8) = 0.004x_{81} + 0.034x_{82} + 0.128x_{83} + 0.102x_{84} + 0.019x_{85} + 0.006x_{86}$$

$$v(x_9) = 0.056x_{91} + 0.015x_{92} + 0.007x_{93}$$

$$v(x_{10}) = 0.027x_{101} + 0.015x_{102} + 0.009x_{103}$$

$$v(x_{11}) = 0.042x_{111} + 0.017x_{112} + 0.006x_{113}$$

$$v(x_{12}) = 0.009x_{121} + 0.018x_{122} + 0.035x_{123}$$

• *Subject to*: $\sum_{j=1}^{12} x_j \leq$ *Available Budget Scenario*

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} \leq \; B_1(450) \;\; or \; B_2(480) \;\; or \; B_3(510)$$

• *Add constraints: Linking constraint relating new variables to old*

$$x_j = \sum_{k=1}^{r_j} x_{jk}$$

• *Include the binary variables and add the bound constraints (if, convex). The bounds have now been converted to the dollar expenditure that represents the percentage at the line segment breakpoint.*

$y_{jk} = 1$ (*if piece k is included) or 0 (not included),*

$$y_{61} = 0 \ or\ 1,\ y_{62} = 0 \ or\ 1,\ y_{63} = 0 \ or\ 1$$

$$y_{81} = 0 \ or\ 1,\ y_{82} = 0 \ or\ 1,\ y_{83} = 0 \ or\ 1$$

$$y_{84} = 0 \ or\ 1,\ y_{85} = 0 \ or\ 1,\ y_{86} = 0 \ or\ 1$$

$$y_{121} = 0 \ or\ 1,\ y_{122} = 0 \ or\ 1,\ y_{123} = 0 \ or\ 1$$

If, convex: $d_1 y_{j2} \le x_{j1} \le d_1$,

$$(d_k - d_{k-1}) y_{j,k+1} \le x_{jk} \le (d_k - d_{k-1}) y_{jk},\ k = 2,\ldots,r_j - 1$$

$$0 \le x_{jr_j} \le (d_{r_j} - d_{r_j - 1}) y_{jr_j}$$

If, concave: $0 \le x_{jk} \le d_k - d_{k-1}$

1) *Attribute j=1 (concave):* $x_1 = x_{11} + x_{12} + x_{13}$

$$0 \le x_{11} \le 13.42,\ 0 \le x_{12} \le 26.84,\ 0 \le x_{13} \le 26.84$$

2) *Attribute j=2 (concave):* $x_2 = x_{21} + x_{22} + x_{23}$

$$0 \le x_{21} \le 15.44,\ 0 \le x_{22} \le 30.88,\ 0 \le x_{33} \le 30.88$$

3) *Attribute j=3 (linear):* $0 \le x_3 \le 59.7$

4) *Attribute j=4 (concave):* $x_4 = x_{41} + x_{42}$

$$0 \le x_{41} \le 11.6,\ 0 \le x_{42} \le 46.4$$

5) *Attribute j=5 (concave):* $x_5 = x_{51} + x_{52} + x_{53}$

$$0 \le x_{51} \le 16.6,\ 0 \le x_{52} \le 8.3,\ 0 \le x_{53} \le 16.6$$

6) *Attribute j=6 (convex):* $x_6 = x_{61} + x_{62} + x_{63}$

$$13.89 y_{62} \le x_{61} \le 13.89 y_{61},\ \ 18.52 y_{63} \le x_{62} \le 18.52 y_{62}$$

$$0 \le x_{63} \le 13.89 y_{63}$$

7) *Attribute j=7 (concave):* $x_7 = x_{71} + x_{72} + x_{73}$

$$0 \le x_{71} \le 13.82,\ 0 \le x_{72} \le 27.64,\ 0 \le x_{73} \le 27.64$$

8) *Attribute j=8 (S-curve):* $x_8 = x_{81} + x_{82} + x_{83} + x_{84} + x_{85} + x_{86}$

$$11.73 y_{82} \le x_{81} \le 11.73 y_{81}, \quad 5.83 y_{83} \le x_{82} \le 5.83 y_{82}$$

$$1.95 y_{84} \le x_{83} \le 1.95 y_{83}, \quad 2.74 y_{85} \le x_{84} \le 2.74 y_{84}$$

$$8.99 y_{86} \le x_{85} \le 8.99 y_{85}, \quad 0 \le x_{86} \le 7.82 y_{86}$$

9) *Attribute j=9 (concave):* $x_9 = x_{91} + x_{92} + x_{93}$

$$0 \le x_{91} \le 7.12,\ 0 \le x_{92} \le 27.27,\ 0 \le x_{93} \le 24.91$$

10) *Attribute j=10 (concave):* $x_{10} = x_{101} + x_{102} + x_{103}$

$$0 \le x_{101} \le 23.44,\ 0 \le x_{102} \le 11.72,\ 0 \le x_{103} \le 23.44$$

11) *Attribute j=11 (concave):* $x_{11} = x_{111} + x_{112} + x_{113}$

$$0 \le x_{111} \le 11.38,\ 0 \le x_{112} \le 22.76,\ 0 \le x_{113} \le 22.76$$

12) *Attribute j=12 (convex):* $x_{12} = x_{121} + x_{122} + x_{123}$

$$22.68 y_{122} \le x_{121} \le 22.68 y_{121}, \quad 22.68 y_{123} \le x_{122} \le 22.68 y_{122}$$

$$0 \le x_{123} \le 11.34 y_{123}$$

All variables are non-negativities, j=1, 2,..., 12

$0 \le x_1 \le 67.1$	$0 \le x_7 \le 69.1$
$0 \le x_2 \le 77.2$	$0 \le x_8 \le 39.1$
$0 \le x_3 \le 59.7$	$0 \le x_9 \le 59.3$
$0 \le x_4 \le 58.0$	$0 \le x_{10} \le 58.6$
$0 \le x_5 \le 41.5$	$0 \le x_{11} \le 56.9$
$0 \le x_6 \le 46.3$	$0 \le x_{12} \le 56.7$

4.2 Budget Scenario Analysis

The MILP is solved (using LINDO 6.1) for high, medium and low budget scenarios in both damage degree levels. Tables 17 and 18 represent a set of funded attributes maximizing the overall value of the MILP for three different budget scenarios for the high and medium damage levels respectively.

Table 17. Result of MILP (High Damage Degree)

Attribute	Demand	Budget Scenario ($\times 1000$ \$)		
		High (510)	Medium (480)	Low (450)
1. Search / Rescue	67.1	67.09 (99.98%)	67.09 (99.98%)	67.09 (99.98%)
2. Emergency Medical Care	77.2	77.19 (99.98%)	77.19 (99.98%)	59.43 (76.98%)
3. Food Aid / Nutrition	59.7	59.7 (100%)	59.7 (100%)	59.7 (100%)
4. Shelter / Non-Food Item	58	58 (100%)	58 (100%)	58 (100%)
5. Sanitation / Hygiene	41.5	41.5 (100%)	37.13 (89.47%)	24.9 (60%)
6. Public Security	46.3	46.3 (100%)	46.3 (100%)	46.3 (100%)
7. Health Service	69.1	41.46 (59.99%)	41.46 (59.99%)	41.46 (59.99%)
8. Economics	39.1	22.29 (57%)	22.29 (57%)	22.29 (57%)
9. Transport	59.3	32.75(55.23%)	7.12 (12%)	7.12 (12%)
10. Public Facilities	58.6	23.44 (40%)	23.44 (40%)	23.44 (40%)
11. Public Utilities	56.9	13.42 (23.58%)	13.42 (23.58%)	13.42 (23.58%)
12. Environment	56.7	26.84 (47.34%)	26.84 (47.34%)	26.84 (47.34%)
Total Amount	689.5	509.98 (73.9 %)	479.98 (69.6%)	449.98 (65.3%)
The overall value		0.889	0.868	0.841

Table 18. Result of MILP (Medium Damage Degree)

Attribute	Demand	Budget Scenario ($\times$1000 \$)		
		High (510)	Medium (480)	Low (450)
1. Search / Rescue	67.1	67.09 (99.98%)	67.09 (99.98%)	67.09 (99.98%)
2. Emergency Medical Care	77.2	77.19 (99.98%)	71.25 (92.3%)	46.32 (60%)
3. Food Aid / Nutrition	59.7	59.7 (100%)	59.7 (100%)	59.7 (100%)
4. Shelter / Non-Food Item	58	11.6 (20%)	11.6 (20%)	11.6 (20%)
5. Sanitation / Hygiene	41.5	41.5 (100%)	41.5 (100%)	41.5 (100%)
6. Public Security	46.3	46.3 (100%)	46.3 (100%)	46.3 (100%)
7. Health Service	69.1	65.51 (94.8%)	41.45 (59.98%)	41.45 (59.98%)
8. Economics	39.1	31.28 (80%)	31.28 (80%)	31.28 (80%)
9. Transport	59.3	34.39 (57.99%)	34.39 (57.99%)	34.39 (57.99%)
10. Public Facilities	58.6	35.16 (60%)	35.16 (60%)	30.09 (51.34%)
11. Public Utilities	56.9	13.42 (23.58%)	13.42 (23.58%)	13.42 (23.58%)
12. Environment	56.7	26.84 (47.33%)	26.84 (47.33%)	26.84 (47.33%)
Total Amount	689.5	509.98 (73.9%)	479.98 (69.6%)	449.98 (65.3%)
The overall value		0.859	0.836	0.812

Since all of the SDVFs are monotonically increasing, in both damage degree cases the overall value increases as the budget amount. In the high damage degree case, all objectives under *Safety of Human Life* were fully funded for all three budget scenarios with the exception of *Emergency Medical Care* and *Sanitation / Hygiene.* The funding levels on the objectives of *Emergency Medical Care, Sanitation / Hygiene*, and *Transport* were affected by the different budget scenarios. In the medium damage degree case, the funding levels for *Emergency Medical Care*, *Health Service*, and *Public Facilities* were affected by the different budget scenarios.

4.3 Summary

This chapter demonstrated how the model proposed in this research could be used to compare the value of relief efforts for several budget scenarios and to determine the optimal resource allocation for each of those scenarios. First, the result of value focused thinking (VFT) was demonstrated based on notional disaster scenario. Then, the resources (budget) were allocated by MILP for the optimal level of attainment over fundamental objectives as maximizing the overall value.

5. Conclusions

5.1 Summary of Research

Disasters threaten nearly every sector of the U.S. society as well as all parts of the world. Threatened areas include (but are not limited to) human life, critical infrastructures and military installations. The disaster cost is at least $20 billion annually in loss of life and property, disruption of commerce, and response and recovery costs (SDR report 2003). Along with the increasing threats, various efforts and methodologies have been suggested to prevent hazards and enable better response to disaster. It is essential that the effective management of humanitarian assistance or disaster relief activities is continuously improved. Through careful planning and application of appropriate information and techniques, communities can be prepared to withstand and recovery from disaster events

This paper described a multi-objective decision-making model for resource allocation in initial disaster relief efforts using Value Focused Thinking (VFT) process and Mixed Integer Linear Programming (MILP). This research focused on developing a model to provide an optimal allocation of scarce resources across a variety of competing objectives and programs to maximize relief effectiveness based on a notional hurricane and flood scenario. This model can provide decision-makers with a tool to determine the optimum allocation strategy for relief resources. This multi-objective decision making framework not only facilitates the resource allocation method, but also identifying the critical elements and criteria of humanitarian or disaster relief to ensure effective relief effort.

In the VFT process, fundamental objectives as primary goals of disaster relief and resource-related means objectives were generated. These objectives provide a basis for establishing the disaster relief value model. A significant disaster may cause injuries to a considerable number of people who require assistance. Providing this assistance requires considerable resources; therefore, the resource allocation problem was identified as a core operation in disaster relief.

In real disaster events, available resources are usually limited and many restrictions exist regarding how these resources can be allocated. The number of alternatives (different allocations) is very large and it is infeasible to score each one. Mathematical programming was introduced as a method to solve the resources allocation problem based on the values expressed in the value hierarchy.

5.2 Strengths of Model

The VFT and MILP model suggest that a set of attributes could be used to determine the resource allocation that maximizes the overall value given a budget. For community leaders, they are unlikely to get all of the resources they desire for disaster relief. This model helps them determine how to allocate the limited budget. The model also provides them with a tool that can be used to evaluate several budget scenarios and use this information in their request for funding. For disaster relief organization, this model provides a structured method to allocate their limited resources to best meet the communities (decision-makers) needs.

5.3 *Recommendation of Future Research*

Although a model of this research has been developed for the efficient allocation and distribution of relief resources, there are a number of unresolved issues and areas for future research. The objectives, measures, SDVFs, and weights are all notional based on assumptions made in this research. Through interaction between relief organizations, community leaders, and disaster relief experts a more accurate value model can be created.

Additionally, sensitivity analysis on the coefficients (weights and slopes) of additive value function could be performed. Because the alternatives are points on a continuum, typical VFT weight sensitivity analysis is not appropriate in the MILP context. In this case a combination of MP and decision analysis methods will need to be explored.

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Vita

Captain Seungbae Park graduated from Korea Military Academy (KMA) in March of 1998 with a Bachelor of German Literature. Upon graduation, he was commissioned as a 2nd Lieutenant, Army Field Artillery Officer. After Officer Basic Course, he was assigned to 2nd Armored Brigade and served as a Fire Direction Officer and Aide-de-Camp of General Commander. After serving three years at there, he entered a six-month Officer Advance Course in Janseoung Korea, then, he assigned to 1st Field Artillery Brigade as a Battery Commander. After serving nine months, he entered also a six-month Officer Advance Course in U.S Army Field Artillery School, Fort Sill in Oklahoma U.S. After Course, he was assigned to 35th Infantry Division in Jeonju Korea. While there he served as a Battery Commander and Operations Officer in two years. In August 2005, he entered the Graduate School of Engineering and Operational Sciences, Air Force Institute of Technology in Ohio U.S. Upon graduation, he will be assigned to ROK Army Headquarters.

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14. ABSTRACT
This thesis addresses the critical resource allocation in the initial days of a disaster relief operation. One of the most important and essential components of relief operations is the allocation of scarce resources to accomplish the relief efforts. Every operation for disaster relief needs various critical resources whether they are personnel, equipment, supplies, or simply finances. Several research efforts for disaster relief have suggested methods to allocate scarce resources across a variety of competing objectives and programs in a disaster relief operation. Many of those efforts focused on optimizing a mathematical programming model subject to budget constraints. However, capturing the values of the decision-maker(s) in such a model is relatively under explored. The lack of clear organizational values contributes to the inconsistency in practice and hinders effective resources allocation across the disaster relief system.

The purpose of this study is to develop a multi-objective decision-making (MODM) model to incorporate the decision-maker(s) value trade-offs in the disaster relief resources allocation problem. The notional model is based on a hurricane and flood scenario and the decision window for the resource allocation is the critical first 72 hours after the initial damage assessment has been made. The value focused thinking (VFT) process is used to capture the value trade-offs and the resulting value hierarchy is optimized via a mathematical programming model to solve the multi-objective resource allocation problem.

15. SUBJECT TERMS
Humanitarian (Disaster) Relief, Resources Allocation, Multi-Objective Decision-Making (MODM), Value Focused Thinking (VFT), Mathematical Programming (MP), Mixed Integer Linear Programming (MILP)

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