Scenario-Based Preferences in Risk Analysis and Systems Engineering: Evolution through Time Frames

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A Dissertation

Presented to

the faculty of the School of Engineering and Applied Science

University of Virginia

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in partial fulfillment

of the requirements for the degree

Doctor of Philosophy

by

Michelle C. Hamilton

May

2014

APPROVAL SHEET

The dissertation

is submitted in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

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Abstract

Priority-setting in large-scale systems involves uncertainties across multiple, competing aims that span technology, climate, economy, regulatory, socio-economic, ecology, and other dimensions. Recent literature has advocated scenario-based preferences in multicriteria analysis to seek robust initiatives across scenarios of epistemic or deep uncertainty (Stewart et al. 2013; Goodwin and Wright 2001; Montibeller et al. 2006 and Parnell 1999). Schroeder and Lambert (2011) adopted scenario-based preferences for risk analysis, identifying combinations of risk factors that are influential to priority setting. Previous analyses fall short of addressing evolving initiatives, criteria, and uncertainties. The scenario-based approach should be implemented as a process that provides continuity of analyses across past, present, and future time frames. This dissertation describes a process for iterative framing of scenario-based preferences for risk analysis in systems engineering, updating criteria, alternatives, and emergent factors. The process is demonstrated in several case studies: (i) selecting energy technologies for islanding of fixed military installations, and (ii) selecting research and development initiatives for climate-change resilience of coastal facilities. The approach is generally applicable for risk analysis and systems engineering that addresses emergent and future conditions for the government, military, and industry.

Acknowledgements

I would like to express my sincerest gratitude to my advisor, Professor James H. Lambert for his guidance and support throughout my doctoral program. I am grateful to my dissertation committee: Professor Peter A. Beling, Professor, Professor Garrick E. Louis, and Professor William T. Scherer of the Department of Systems and Information Engineering, and Professor Lisa M. Colosi Peterson of the Department of Civil and Environmental, for their invaluable knowledge and assistance.

I am grateful to all the faculty and staff of the Department of Systems and Information Engineering of the University of Virginia for their guidance and the opportunity to pursue this degree. I am grateful to US Army Corps of Engineers Engineer Research and Development Center (USACE ERDC) for providing case studies and supporting data, presentation opportunities, and other support for this research.

I am grateful to my parents, Michael and Pamela Gaudiose for their support and understanding of all my life. I thank my husband Wayne Hamilton for providing unrelenting support throughout the development of my research. Finally, I thank my colleagues in the Center for Risk Management of Engineering Systems for their friendship, motivation, and support.

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Notation

A	set of N initiatives to be prioritized
a_i	i^{th} initiative
I	set of m frames of scenario based preference multicriteria analysis
I^t	Frame at time t of scenario-based preference multicriteria analysis
T	robustness threshold scenario
$m(s_j)$	measure of ranking disruptiveness of j^{th} scenario
O^t	set of outputs for scenario-based preference frame t
$r_{i,j}$	ranking value of i^{th} initiative in j^{th} scenario
$rb(a_i)$	robustness measure of initiative a_i
S	set of J+1 stakeholder scenarios
s_0	baseline scenario
s_j	j^{th} stakeholder scenario
$v_k(\bullet)$	k^{th} criterion value function
$V_j(\bullet)$	j^{th} scenario additive value function
Z	criteria space of K criteria
Z^k	k^{th} criterion space
z_i^k	measure of attainment in the k^{th} criterion for the i^{th} initiative
z^{ko}	least preferred level of Z^k
z^{k*}	most preferred level of Z^k
$\succcurlyeq$	preference-indifference binary relation
α	worth multiplier
λ_k	normalized k^{th} criterion coefficient of the baseline value function $V_0(\bullet)$
$\lambda_{j.k}$	normalized k^{th} criterion coefficient of the $V_j(\bullet)$
$\lambda'_{j.k}$	non-normalized k^{th} criterion coefficient of the $V_j(\bullet)$

Chapter 1 : Introduction

1.1 Overview

This chapter introduces the topic of the dissertation. The chapter describes the problem statement, the philosophy of the approach, and the organization of the dissertation.

1.2 Problem Statement and Philosophy

Priority setting for infrastructure systems involves multiple, competing objectives, and uncertainties in the state of the world that can span technology, climate, economy, regulatory, socio-economic, ecology, and other dimensions. Moreover, priorities are often influenced by views, values, and concerns that are either contradictory or not made explicit. Recent developments in risk analysis and scenario-based preferences address these challenges of strategic design of infrastructure systems, particularly the key question of how to anticipate the future in a structured, integrated, participatory, and policy-relevant manner. In a context of systems engineering, analysis of scenario-based preferences contributes a timely understanding of future and emergent conditions and helps to avoid regret and belated action. Past efforts have combined multicriteria analysis with scenario planning for strategic design (Hamilton, 2013a, 2013b, Stewart et al. 2013, Karvetski et al 2012, 2011a, 2011b and 2011c; Schroeder and Lambert 2009; Goodwin and Wright 2001; Montibellier et al. 2006 and Parnell 1999). The focus of past research has been to identify robust alternatives across scenarios of epistemic or deep uncertainty. Schroeder and Lambert (2011) describe that scenario-based preferences in multicriteria analysis can be used in risk analysis to identify scenarios that are influential to priority-setting as both threats and opportunities. In this context, *scenarios* are defined as combinations of conditions that influence the preference functions of stakeholders. This work builds on the 2009 International Standards Organization (ISO) definition of *risk* as *the impact of uncertainties on objectives* (ISO 2009) and, subsequently, Schroeder and Lambert (2012), Karvetski and Lambert (2012) and Karvetski et al. (2011a, 2011b, 2011c, 2011d, 2009, Lambert et al. (2012, 2011a; 2011b; 2011c; 2011d; 2010), 2012, You et al. (2013), Hamilton et al. 2013a; 2013b; 2014a, Hamilton and Lambert 2014 (submitted to *Reliability Engineering and System Safety*) and Hamilton et al. 2014b (submitted to ASCE-ASME Journal of Risk and Uncertainty) who introduced *risk* in a new aspect as *the influence of scenarios to priorities*. Scenario-based preferences in multicriteria analysis has since been applied to energy infrastructure, climate change, water infrastructure, airline safety, transportation, and others to identify uncertainties that are the most influential to decision making. To date each of the applications has been a static, one-time analysis. In contrast, many in the systems engineering community have recognized that problem definition co-evolves with the exploration of options (e.g., Zeleny, 2011). Risk, decision, and optimization models, among others, are transient instances of the current states of knowledge of initiatives, criteria, measurable and non-measurable outcomes, stakeholder preferences, information inputs, and uncertainties.

This dissertation addresses the need for extending risk analysis and scenario-based preferences analysis beyond static analysis, described above, to an iterative approach. The focus of this dissertation is to re-aim the priority-setting problem (via updates of criteria, initiatives, and emergent and future conditions) in subsequent frames. The approach will iteratively guide expert and stakeholder elicitation to the conditions and scenarios that are most influential to priority setting, and provide continuity of analysis from time frame to time frame.

The philosophy can be described in more detail as follows: The aim of scenario-based preference analysis has been to prioritize a set of $A = \{a_1, ..., a_n\}$, of n initiatives to obtain an ordering $a_{n_1} \succcurlyeq \cdots \succcurlyeq a_{n_n}$ under each considered scenario, where $\succcurlyeq$ denotes preference-indifference. The ordering $\{n_1,\ldots n_n\}$ is a permutation of $\{1,...,n\}$. The initiatives are not necessarily exclusive. In practice, the top-five, top-ten, bottom-ten, etc., initiatives are of particular interest for resource allocation.

Scenario-based preference analysis for any given time period thus involves the following elements:

(i) A set of initiatives A = $\{a_i\}$;

(ii) A set of criteria Z = $\{Z^k\}$;

(iii) A set of scenarios S = $\{s_i\}$

Karvetski et al, 2009, Karvetski and Lambert (2012), You (2013) and Schroeder and Lambert (2011) use scenario-based preference analysis to identify scenarios that are most influential to priority setting. This dissertation extends the static approach of Karvetski et al. (2009), Karvetski and Lambert (2012), You et al. (2013) and Schroeder and Lambert (2011) to an iterative approach. The iterative risk assessment across time frames is defined as a $\mathbf{I} = \{I^1, I^2,...,I^m\}$. Each frame $I^t \in \mathbf{I}$ has structure as a three-tuple $\{A^t, Z^t, S^t\}$ where A^t is the set of initiatives to be prioritized at time frame t; Z^t is the set of criteria for evaluating and prioritizing the initiatives at time frame t; and S^t is the set of scenarios at time frame t. Each time frame I^t produces output O^t which describes a robustness measure for each initiative in A^t and the degree of influence or disruptiveness for each scenario in S^t. Each time frame I^{t+1}, will use the output O^t to refine the elements $\{A^{t+1}, Z^{t+1}, S^{t+1}\}$ that are a subset of those in time frame I^t. For each time frame, refinements are made to either select robust initiatives for detailed design, to address a subset of robust alternatives to further distinguish another as preferred, and/or to focus investigations and studies on a subset of scenarios that most influential to the prioritization of initiatives

The aim of this dissertation is to develop principles and a process for applying scenario-based preference modeling across time frames. The process is demonstrated two case studies. This is accomplished by a simultaneous focus on risk and robustness outputs of each frame of scenario-based preference analysis. Each time frame of analysis should support an evolving multidimensional (economic consequences, safety consequences, environmental consequences, etc.) risk analysis with insight to conditions and factors that influence priority-setting, and thus are warranting additional science or engineering studies.

Complementary to the traditional concern of risk analysis for the likelihoods and outcomes of adverse effects, this approach supports the interface of risk analysis to systems design innovation -- with the spurring of new and improved initiatives. Each time frame of scenario-based preference analysis will provide outputs that can be used for subsequent time frames to: (i) refine the initiatives, (ii) refine the criteria of priority setting, (iii) refine the scenarios (built from emergent and future conditions), (iv) refine the parameters of related studies, and activities, such as simulation modeling, process optimization, lifecycle analysis, systems integration, etc.

1.3 Organization of Dissertation

The organization of the dissertation is as follows. Chapter 2 will discuss the background and literature related to scenario-based preference multicriteria analysis, risk analysis, and scenario analysis. A significant portion of the literature review focuses on a core set of papers on which this dissertation builds its philosophy. Chapter 3 presents the methods of the dissertation. It begins with a mathematical model and connects the iterative philosophy to the modeling inputs and outputs of scenario-based preference analysis. Chapter 4 presents a case study on energy security decision-making at military installations. Chapter 5 presents a case study on climate change decision making for coastal regions. Chapter 6 is a discussion of key assumptions and limitations. Chapter 7 presents a summary and conclusions, which includes research contributions and future work.

Background and Literature Review

2.1 Chapter Overview

This chapter provides background and motivation for a risk analysis with scenario-based preference to evolve in multiple time frames. This chapter will review literature on risk analysis, scenario analysis, integration of multicriteria decision analysis and scenario analysis, robust decision-making, and systems analysis concepts.

2.2 Risk Analysis for Infrastructure Systems Engineering

Risk has been defined as the measure of the probability and severity of adverse effects (Lowrance 1976). This definition was refined by Kaplan and Garrick (1981) to include the three canonical questions: what can go wrong, what are the likelihoods, what are the consequences. Haimes (1991) defined risk management as what can be done in what time frames, what are the tradeoffs, and what are the impacts of current decisions on future options. Recently, ISO 31000 (2009) defined risk to be the effect of uncertainty on objectives. This shift in emphasis was to accommodate both negative and positive possibilities. Schroeder and Lambert (2012), Karvetski and Lambert (2012) and Karvetski et al. (2011a, 2011b, 2011c, 2011d, 2009, Lambert et al. (2012, 2011a; 2011b; 2011c; 2011d; 2010), You et al. (2013), Hamilton et al. 2013a; 2013b; 2014a, Hamilton and Lambert 2014 (submitted to *Reliability Engineering and System Safety*) and Hamilton et al. 2014b (submitted to ASCE-ASME Journal of Risk and Uncertainty) have defined risk to be the *influence of scenarios to priorities*. This latter definition is in contrast to the notion that risk assessment in systems engineering can objectively address the three canonical questions: What can go wrong, what is the likelihood, and what are the consequences (Karvetski and Lambert 2012)? Often when in the early stages of strategic design, assigning probabilities to scenarios can be problematic since the scenarios may not be quantitative, exhaustive or mutually exclusive, and probability estimates may differ across stakeholders (Karvetski and Lambert 2012). Rather than events in a probability space, the scenarios are deep, structural uncertainties, and stakeholders do not know or have consensus on the definition or influence of scenarios (Bryant and Lempert 2010; Karvetski et al., 2012). Such uncertainty, often termed deep uncertainty, is characterized by unavailability of risk models that assess the probabilities of future outcomes; disagreement about the likely impacts of alternative options; and uncertainty about available alternatives, resulting in a premature focus on salient initiatives instead of devising better options (Ram and Montibeller, 2013). Cox (2012) discusses that when confronted with deep uncertainty, robust risk analysis methods shift the emphasis of the questions that define risk analysis from passive (What might happen, and how likely is it?) to more active (How should I act, now and in the future?).

The definition of risk as articulated by Lambert et al. (2012) recognizes that one of the objectives of risk analysis is to determine which uncertainties change the priorities placed on various strategic options so that one can better answer the active questions posed by Cox (2013) (i.e. How should I act, now and in the future?). With this definition of risk, modeling efforts are aimed at providing a principled framework to sequence stakeholder discussions and design activities in order to understand which initiatives are robust to various scenarios/perspectives as well as to determine which scenarios matter most in terms of priority-setting among R&D activities and investment. The modeling effort is not focused on an optimized decision, but rather on insight into the risks and opportunities associated with influential scenarios.

One approach to risk modeling under conditions of deep uncertainty is the use of scenario planning. The next section will review literature of scenario planning.

2.3 Scenarios for Infrastructure Systems Engineering

In strategic problems, decisions must be made between alternatives investments in the short term, but the investment time horizon is often such that significant uncertainties exist about future states of the world and the value of alternatives may depend on which state(s) of the world eventually occur (Parnell, 1999). As discussed in the previous section, the standard approach to uncertainty is to identify mutually exclusive and collectively exhaustive outcomes and assign probabilities to each outcome. Unfortunately, in strategic decision settings, the description of possible futures are seldom collectively exhaustive (Karvetski and Lambert, 2012). Scenario planning is an alternative technique to examine the uncertain future and is an especially useful and attractive tool in strategic decision-making made popular by Van der Heijden (1996) and his colleagues at Shell. Scenario planning enables the characterization of possible threats and opportunities related to a system that can span technology, climate change, economy, regulatory, socio-economic, ecology, and others. Unlike forecasting, scenario planning provides a means of addressing uncertainty without the use of probabilities. Furthermore, scenario planning enables the observation of joint impacts of various uncertainties, simultaneous changes in various variables, and uses subjective interpretations beyond the reach of objective analysis (Schoemaker, 1995). Although it is not possible to fully characterize the potential futures, scenario planning provides a way to reduce the uncertainties to a reasonable number of factors that most matter to decision making. Ultimately, the decision maker is able to define strategies that are robust over a range of different possible outcomes (Belton and Stewart, 2002; Goodwin and Wright, 2001, Montbellier, 2006, Karvetski and Lambert, 2012, Karvetski et al., 2011a, 2011b, 2011c, 2010, 2009). Karvetski and Lambert (2012) describe scenarios using the concept of *mise-en-scène*. Mise-en-scène, literally, "putting forth a scene" is used in the arts (film, literature, and elsewhere) to describe the projection of imagery and emotion of a scene onto the audience through the arrangement of any and all elements. According to Lambert and Karvetski (2012) "In stakeholder engagement, the scenarios are similar to mise-en-scènes in that they describe events of risk and uncertainty, but they can also be associated with evocative and emotional narrative [Corvellec and Risberg, 2007]."

Stewart et al. (2013) describes several definitions of scenarios: (1) The Shell Scenario Planning Approach (Van der Heijden 1996) where the emphasis of scenarios is on constructing a coherent story of the future context (external events) against which policies are compared and evaluated. The scenarios provide a basis for a strategic conversation concerning pros and cons of strategic decision options. It is stressed in this approach that policy options do not form part of the scenario; (2) Scenarios for exploring uncertainty where scenarios may be used to explore how different uncertainties may play out but there are no identified strategies needing to be evaluated against them. Here possible futures are explored to stimulate discussion about whether a change in strategy is necessary or whether there are opportunities that might be capitalized upon; (3) Scenarios for advocacy or political argument where policy decisions are now explicitly included in the scenario, in order to emphasize plausible consequences of the policy directions. The purpose of the scenario is to create a narrative that highlights either the benefits or dangers of following a policy. (4) Representative sample of future states where future states are conceptualized in terms of a multivariate probability distribution on the state space. Since complete distribution may never be fully identified, often analysis is based on a small number of representative outcomes in the sample space.

The next section describes the benefits of integrating scenario planning with multicriteria analysis. In common with scenario planning, a primary requirement of scenarios to be used in multicriteria analysis is to provide a description of the context within which the consequences of any policy action will be played out (Stewart et al. 2013). As the purpose of the decision analysis is to evaluate and compare actions or policies, scenarios should reflect external driving forces (events, states, exogenous parameters), which are separated from the policies or actions under consideration.

2.4 Integration of Risk Analysis and Scenario-Based Preferences

Recent developments in the area of scenario-based preferences in multicriteria analysis have provided an alternative to traditional decision analytic techniques such as decision trees that require the use of subjective probabilities. The aim of these methods is to identify investment initiatives that are the most robust across the alternate futures. These newer methods are flexible, versatile and transparent and lead to a clear and documented rationale for the selection of a particular strategy (Goodwin and Wright, 2001, Montbellier, 2006, Karvetski and Lambert, 2012).

Stewart discussed the benefits of integration of scenario analysis and multicriteria analysis. In the problem structuring, value elicitation and strategy construction phase of multicriteria analysis, a focus on distinct scenarios can provide participants greater clarity of thought, communication, and exploration of contingencies (French et al. 2009; Stewart et al. 2013). It may highlight sources of conflict between participants perhaps because each may have been anchoring preferences based on different scenarios. Finally, it can stimulate creative thinking to help design strategies that perform well across scenarios.

Goodwin and Wright (2001) developed an approach that is an extension of a traditional multiattribute value theory analysis, where they defined a set of *n* strategic options (a_i), a set of *m* future scenarios (s_j); and each decision alternative was a combination of strategic options in a given scenario (a_i-s_j). Next they define a value tree, which represents the fundamental objectives of the organization and measures the achievement of each decision alternative a_i-s_j on each objective of the value tree using a 100-0 value scoring. They elicit weights of each objective in the value tree using swing weighting (anchoring on the worst and best decision alternatives). They aggregate the performance of each decision alternative a_i-s_j with the weights attached to the objectives in the value tree to find an overall score for the decision alternative. However, since the decision alternatives are evaluated on combinations of alternatives and scenarios, this does not give an indication of which alternatives are robust across scenarios.

Montibeller et al. (2006) applied the Goodwin and Wright approach to two case studies and found that decision makers struggled to provide preference information (criteria weights and alternatives' performances) due to the complexity of having to analyze strategy-scenario pairs, as required by the Goodwin & Wright approach. They also found that addressing situations where stakeholders' priorities changed under different scenarios was lacking in the Goodwin and Wright approach.

Montibeller et al. (2006) propose some extensions of splitting of the MCDA model, creating a model for each scenario, which permits an easier assessment of options and the possibility of using different weights and criteria for each scenario. This adaption allows them to measure the inter-scenario risk of each option, as well as assess inter-scenario robustness. Ram et al. (2011) incorporate 12 diverse scenarios to a multicriteria framework to evaluate food security options in Trinidad and Tobago by creating an additive value function for each scenario. The elicitation process is entirely replicated for each scenario and a monetized regret or mini-max measure is used to evaluate the robustness of the alternatives after the value differences are rescaled using a value-cost equivalency. This rescaling allows for the value differences of the same alternative to be compared across different scenarios. The repetition and the time demand of the elicitation process are chief complaints of the interviewed decision maker after a few scenarios.

Schroeder and Lambert (2012), Karvetski and Lambert (2012) and Karvetski et al. (2011a, 2011b, 2011c, 2011d, 2009) adopt the concept of scenario-based preferences for risk analysis. In their approach, scenarios are introduced to change the relative importance of particular criteria among others, particular to each scenario above and beyond a baseline scenario. The stakeholder is not asked to reweight the criteria, but rather to assess whether the importance of a criterion increases, decreases, or stays the same This change in importance is incorporated into a change in its weight. The new weights represent the weights of the criteria given that a particular scenario is observed, thus each scenario is represented by a unique set of criteria weights. For each scenario, a new value function is calculated for each alternative. Outputs from this type of analysis can identify alternatives that are robust across scenarios, and, more importantly, identifies scenarios that are most disruptive or influential to the ranking of alternatives to which additional modeling, information-gathering, and other resources should be applied. An innovation of this method is that many scenarios can be explored while keeping the elicitations of additional preference information relatively few. Each scenario can represent the view of an individual stakeholder or organization. Scenarios addressed in this approach are typically narrative and qualitative descriptions and are described using the concept of mise-en-scène, literally, *putting forth a scene,* as described in Karvetski and Lambert (2012).

Stewart et al. (2013) describes a need for preference aggregation across both criteria of evaluation and scenarios. The authors suggest several guidelines in constructing scenarios for multicriteria decision analysis:

1. About 4-6 scenarios need to be constructed.
2. The scenarios must be defined in terms of exogenous drivers.
3. The scenarios need to cover ranges of outcomes expected as well as key associations between the variables.
4. In circumstances in which there are substantial differences between the fundamental values of stakeholders there may be an advantage in using scenarios that represent different ideal worlds.

The authors present a framework for structuring the aggregation. They base the framework on the assumption that in a scenario-based multicriteria decision analysis structure alternatives fundamentally need to be evaluated and compared in terms of all mxp performance measures. Attention needs to be given to how well an alternative performs in terms of each criterion under the conditions of each scenario. The authors reference criterion-scenario combination as a metacriterion. They create a method to derive separate partial value functions for each metacriterion. They suggest swing weighting through a hierarchical assessment. Two approaches are suggested: Approach 1: For each scenario r, compare the importance swings for each of the m criteria within this scenario, giving estimates of the ratios w_{rj}/w_{kr} for all pairs of criteria, j,k: then for one or two of the more important criteria, compare the relative importance of the swings for these criteria across each of the p scenarios. Approach 2: For each criterion j, compare the importance swings of the criterion j within each of the p scenarios, giving estimates of the ratios w_{jr}/w_{jt} for all pairs of scenario, r, t; then for one or two selected scenarios, compare the relative importance of the swings for each of the m criteria. Thus a final aggregate value can be calculated for each alternative across all scenarios.

The output of the integration of multicriteria analysis and scenario analysis is a preference score for each initiative under each scenario (or an aggregate score across scenarios as described by Steward et al. (2013). The next section discusses how this output supports robust decision-making.

2.5 Robust Decision Making

Robust decision-making is an iterative and analytic process that (1) identifies strategies whose performance is largely insensitive to poorly characterized uncertainties, and (2) identifies a small number of scenarios representing uncertainties that are relevant to the choice of strategies (Lempert et al. 2003; Groves and Lempert 2007). Researches at RAND Corporation developed the robust decision making (RDM) approach based on statistical cluster-finding algorithms to identify regions of parameter or probability space where alternative decisions have significantly different performance (Groves and Lempert, 2006).

Researchers of multicriteria analysis applied the idea of robustness to minimize variability of outcomes across scenarios and/or avoid extreme negative consequences (Stewart et al. 2013). In these applications, scenarios influence the criteria preferences (Montibeller et al. 2006; Ram et al 2011, 2013). Heretofore, robustness to *preferences*, i.e., scenario-based preferences, has not been a topic in the field of robust decision-making.

Previous applications of scenario-based preference analysis have assumed that scenarios are identifiable a priori. This dissertation suggests that scenario identification can evolve with each iteration of scenario-based preference analysis. In Chapter 3, Section 3.3 will discuss several metrics that can be applied to identify robust initiatives. Section 3.4 will discuss several metrics that can be applied to identify the influential scenarios that matter most to decision making. Section 3.5 will discuss how the identification of robust strategies and relevant scenarios can be used to reframe the problem.

2.6 Problem Structuring in Multiple Time Frames

The early phases of infrastructure systems engineering consist of the problem definition, the creation of a value framework and structuring of high-level objectives, the creation of alternatives, the evaluation of alternatives within the value framework, and the refinement of alternatives (Sage and Armstrong. 2000). Montibeller and Franco (2010) discuss the merits of using facilitated multicriteria decision analysis to aiding strategic decisions. They discuss a decision model as a *transitional object* in which stakeholders can share strategic concerns; increase their individual understandings of issues; appreciate the potential impact of different strategic choices; and negotiate strategic action that is politically feasible. Participants' interaction with the model reshapes the analysis, and the model analysis reshapes the group discussion. Kahneman (2002) describes that the exploration of the discrepancy between holistic judgment and a decision model's results links people's emotional and deliberative systems, helping them to access their experience and knowledge, make it explicit and work on it with the help of the group. Phillips (1984) suggests that that these models are *requisite* in that they are at best conditionally prescriptive; they suggests what could be done given the frame, assumptions, data and judgments. Similarly, Wright and Goodwin (1999) suggest that values are not sufficiently well formed in early stages and that one needs some interaction with alternatives to understand values, and values and criteria are formed out of experience with alternatives. Corner et al. (2001) suggests a dynamic approach to problem structuring and that *thinking about values helps generate alternatives* and *thinking about alternatives helps generate values*.

With a purpose of systems engineering and risk analysis and management to design and/or select initiatives that meet objectives in a variety of futures, thinking about scenarios can aid stakeholders in the discovery of values that have not yet been considered in the multicriteria evaluation of alternatives. This provides motivation for the extension of these concepts of dynamic multicriteria analysis to scenario-based preference models. In other words that: *thinking about criteria helps generate scenarios*; *thinking about scenarios helps generate criteria*; and *thinking about scenarios helps generate alternatives.* This dissertation fills a gap in previous literature by asserting that scenarios are not predefined and static; but evolve through multiple time frames of analysis.

2.7 Chapter Summary

While the use of scenario-based preferences in multicriteria decision analysis has been discussed in the literature and applied in practice, the past research has focused on finding robust alternatives in a one-time analysis. Current literature on this specific topic thus highlights a gap to provide for identification of risk scenarios that are most relevant to the choice of strategies ***via scenario-based preferences analysis, in multiple time frames.***

: Methods

3.1 Chapter Overview

This chapter will describe the technical approach of this dissertation. Section 3.2 will first describe a scenario-based multicriteria decision analysis model. Section 3.3 will discuss the metrics which can be used to measure the robustness of initiatives. Section 3.4 will discuss the metrics, which can be used to measure the influence or disruptiveness of scenarios. Section 3.5 will provide a new set of qualitative questions to ask after each time frame to promote productive reframing of the decision problem. Section 3.6 will discuss stakeholder engagement and traceability.

The approach addresses *a key challenge of this effort, which is to describe and test practical* rules of thumb *for performing iterative multicriteria scenario-based preferences analysis* in order to complement overall risk analysis and systems engineering efforts. The tasks thus identify and integrate principles for iterative refinement and evolution through time frames. The refinement is guided by both quantitative (e.g., measurement of robustness of priorities and influence of scenarios) and qualitative activities of previous frames.

3.2 Static Model

The initial, static, phase of scenario-based preference modeling assumes that an organization is seeking to prioritize their resources over many potential investments in order to achieve high-level organizational objectives. These investments can be in the form of technologies, policies, assets, projects, etc. It is assumed that the timeframe for making the decision has been established and several key stakeholders and experts' opinions have been identified as participants. The multiple stakeholders have identified a set of $A=\{a_1,...,a_N\}$ initiatives that they would like to prioritize. The prioritization is represented as a priority order or ranking, $a_{n_1} \succcurlyeq \cdots \succcurlyeq a_{n_N}$, where $\succcurlyeq$ denotes preference-indifference and the ordered set $\{n_{1,...}n_N\}$ is a permutation of {1,…N}. The highest preferred initiative or highest several initiatives would be selected. A multicriteria analysis can be used to generate a priority order of the initiatives (e.g., Keeney and Raiffa, 1993). To evaluate and compare each initiative, a set $Z = \{Z^1,…,Z^{k}\}$ of k performance criteria is used.

For each criterion Z^k a value z^k indicates a level of achievement of the criterion. An initiative is assigned a value score $v_k(a_i) = v_k(z_i^k)$ for each criterion. The value function $v_k(\bullet)$ is scaled such that $v_k(z_i^{ko}) = 0$ and $v_k(z_i^{k*}) = 1$, for k = 1, …,K. Here z^{ko} represents the least preferred level in the k^{th} criterion and z^{k*} represents the most preferred.

An additive multicriteria value function can be used to account for tradeoffs across criteria and generate prioritization of initiatives across K criteria. The additive form of the multicriteria value function has the form

$$V_0(a_i) = 100 * \sum_{k=1}^{m} \lambda_k v_k(a_i) \text{ with } \sum_{k=1}^{m} \lambda_k = 1 \text{ and } 0 \leq v_k(a_i) \leq 1$$

for all k = 1,…,K; i= 1,…N

The set of coefficients $\{\lambda_1, \dots, \lambda_k\}$ represent the tradeoffs across the criteria (Belton and Stewart, 2002). The coefficients can be assessed with multiple methods including swing-weighting. In general, $V_0(a_i) \geq V_0(a_1)$ implies initiative a_i is at least as preferred as initiative a_1. The subscript zero represents this value function as a *baseline* value function for a baseline scenario. The baseline scenario is defined for as the future time period from now until the defined time horizon such that no event occurs during this time period that

1.) Changes any $v_k(z_i^k)$
2.) Changes any $\lambda_k \in \{\lambda_1, \dots, \lambda_k\}$
3.) Changes the additive independence assumptions of the baseline value function

Next, a set $S=\{s_0, s_1, \dots, s_j\}$ of J + 1 scenarios is constructed and used to reflect future uncertainty and the viewpoints of the multiple stakeholders serving as decision makers. It has been shown that a single baseline value function is not sufficient to describe the preference and tradeoffs across all scenarios and these can be scenario-dependent (Montibeller et al. 2006).

With scenario-based preferences, each scenario $s_j \in S$ is represented in the analysis by a value function $V_j(\bullet)$. A unique value function for each scenario can describe changes in preferences or strategies based on each scenario, where each scenario represents the views of one or more stakeholders. An objective of the scenario-based multicriteria analysis is to elicit the set of value functions $\{V_j(\bullet): s_j \in S\}$. Karvetski et al. (2009) introduce an efficient method for deriving the set of value functions $\{V_j(\bullet): s_j \in S\}$ using the swing weighting method. Although each value function $V_j(\bullet)$ representing $s_{j,\, j} \neq 0$, could be derived by starting over with the elicitation of preference information for that scenario, there are time and resource-saving advantages to deriving $V_j(\bullet)$ through minimal elicitation using adaptive adjustment to the baseline value function $V_j(\bullet)$ (Karvetski et al., 2009). The method focuses the adaptive elicitations on the λ-coefficient values. For each scenario, $s_j \in S$, which modifies preferences, $j \neq 0$, the coefficients $\{\lambda_1, \ldots, \lambda_k\}$ of the criteria are increased or decreased to account for how preferences and tradeoffs change. If λ_k increases under scenario s_j compared to the baseline scenario the coefficient of this criterion is adjusted through defining a constant $\alpha > 1$ and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k^{th} criterion is then

$$\lambda'_k = \alpha \times \lambda_k.$$

If, λ_k decrease under scenario s_j compared to the baseline scenario a new non-normalized coefficient for the kth criterion is then

$$\lambda'_k = \frac{1}{\alpha} \times \lambda_k.$$

Normalizing provides a new set of coefficient values $\lambda_{j,1}, \ldots, \lambda_{j,k}$ for scenario s_j, yielding,

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{ with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

$$\textbf{for all k = 1,...,K; i= 1,...N.}$$

This method results in each initiative having a different value score under each scenario. The value score within a scenario provides a means for identifying robust or near robust initiatives. Once all scenarios are included, each initiative a_i receives a ranking value $r_{i,j}$ in the jth scenario using $V_j(\bullet)$, defined for initiative a_i as one plus the number of initiative that are more preferred to a_i in scenario s_j. For the multiattribue value model described above, only ordinal information is assumed and strengths of preferences is not assumed. The value score of an initiative a_i in two different scenarios will not necessarily be comparable with this method of scenario-based preferences. In other words, $V_j(a_i) \geq V_d(a_i)$ does not necessarily mean that a_i in scenario s_j is at least preferred as a_i in scenario s_d. However, some have provided a means to remap or rescale into a common scale (Ram et al, 2011 and Stewart 2013).

After this modeling process, a decision must be made to select a set of high-priority initiatives for detailed design, select a subset of initiatives to further prioritize and distinguish one as preferred, and/or *to select a subset of scenarios for* *additionally detailed analysis*. Thus metrics derived from the output of this model should be defined to identify robust initiatives. This is explored in more detail in the next section.

3.3 Robustness Analysis via Scenario-Based Preferences

It is assumed that it is desirable to select initiatives that perform well across scenarios, i.e. robust initiatives.

Roy (2010) discusses several measures for robustness. The first measure is termed *absolute robustness* where the measure that must be maximized is defined by the value of the solution in the worst scenario. For scenario-based preference analysis, absolute robustness could be interpreted as the largest ranking value across scenarios, $rb(x) = \max_{s_j \in S} r_{i,j}$. This metric interprets robustness in terms of the maximum number of initiatives that are preferred to an initiative across scenarios. The most robust initiative would be the minimum $rb(x)$.

A second measure of robustness that Roy (2010) discusses is *absolute deviation*. The measure that must be minimized is defined by the value of the absolute regret in the worst scenario: $rb(x) = \max_s[V_s^* - V_s(x)]$, where V_s^* is the value of the optimal solution in scenario s. The most robust initiative would be the minimum $rb(x)$. This is similar to the measure of robustness described by Montibeller et al. (2006).

A third measure of robustness that Roy (2010) discusses is *relative deviation*. The measure that must be minimized is defined by the value of the relative regret in the worst scenario, $rb(x) = max_s [(V_s^* - V_s(x))/ V_s^*]$. The most robust initiative would be the minimum $rb(x)$.

A fourth measure of robustness can be defined as a level or threshold, T, that the decision maker asks to exceed (or not to exceed) in the greatest possible number of scenarios. For example, a decision maker might choose to maximize the number of scenarios where the ranking, $r_{i,j}$, is three or less. In other words, the decision maker considers the top three prioritized initiatives to be acceptable. Thus, in this case $rb(x)$ = number of scenarios such that $r_{i,j}$, is greater than T. The most robust initiative in this case would be the initiative with the maximum $rb(x)$.

Others suggest that robustness can be better assessed if preferences are rescaled into a common scale across scenarios. Ram et al. (2011) incorporate twelve diverse scenarios to an MCDA framework to evaluate food security options in Trinidad and Tobago by creating an additive value function for each scenario. The elicitation process is entirely replicated for each scenario and a monetized regret or mini-max measure is used to evaluate the robustness of the alternatives after the value differences are rescaled using a value-cost equivalency. This rescaling allows for the value differences of the same alternative to be compared across different scenarios. Decision makers who provided feedback from this process described that the process was repetitive and time-consuming.

Stewart et al. (2013) describes a need for preference aggregation across both criteria of evaluation and scenarios. As discussed in Section 2.4, the authors present a framework for structuring the aggregation and thus a final aggregate value can be calculated for each alternative across all scenarios as follows:

$$V(a_i) = \sum_{j=1}^{J} \sum_{k=1}^{K} w_{j,k}\, v_{j,k}(a_{ijk}), \text{ with } \sum_{k=1}^{K} w_k = 1 \text{ and } 0 \leq v_{j,k}(a_{ijk}) \leq 1$$

for all k = 1,…,K; j = 1,…J; I = 1,…N

In this formulation, the most robust initiative would be the one with the largest $V(a_i)$.

3.4 Risk Analysis via Scenario-Based Preferences

As mentioned in Chapter 2, risk can be defined as the influence of uncertainty on priorities. The risk metrics used in this dissertation are based on this concept. Metrics are needed to measure the amount of risk that each scenarios has on agency priorities. In the context of scenario-based preferences, Karvetski et al. (2012) and You et al. (2013) suggest a measurement to identify scenarios that are most influential, $m(s_j)$, as the sum of square metric defined as:

$$m(s_j) = \frac{\sum_{i=1}^{I} (r_{i,0} - r_{i,j})^2}{\gamma},$$

where $r_{i,0}$ is the ranking value of initiative a_i in the baseline scenario and $r_{i,j}$ is the ranking value in the jth scenario. The coefficient γ is introduced to normalize the value of $m(s_j)$, so that it is bounded on the interval [0,1]. The coefficient γ is given by the value of $m(s_j)$ when the initiative priorities are fully inverted (see You et al. 2013 for full explanation).

$$\gamma = \frac{n(n^2 - 1)}{3}$$

A scenario with a large $m(s_j)$ values indicates that the scenario is influential in changing priorities. This metric is straightforward to implement. It appropriately exaggerates large jumps or falls in initiative rankings. This metric however, does not give an indication of the scenarios that changed the priority of the top few initiatives, the bottom few, and other ways of looking at the interpreting what constitutes an influential scenario.

In other contexts, the objective of the decision problem may be to select the top T initiatives as opposed to selecting just one. In this case, then appropriate measurement for the disruptiveness or influence of a scenario may be the sum of the number of initiatives that are ranked in the top T initiatives in baseline scenario but not rank among the top T initiatives under scenario s_k, divided by T. This can be expressed as a percent change.

A third metric for identifying influential risk scenarios is to account for those scenarios that provide the largest decrease in an initiative's ranking compared to the baseline ranking. This metric is useful for the iterative problem framing because it allows stakeholders to reflect on how to redesign the initiative to perform better under the threat scenario(s).

A fourth metric for identifying influential risk scenarios is to account for those scenarios that provide the largest increase in an initiative's ranking compared to the baseline ranking. This metric is useful for the iterative problem framing because it allows stakeholders to reflect on the merits of this initiative under the scenario and whether elements of the initiative can be incorporated with other more highly prioritized or robust initiative to creatively design better initiatives.

3.5 Evolution of the Analysis in Several Time Frames

This task will extend the static scenario-based preference methodology and define an iterative risk assessment across multiple time frames as $\mathbf{I} = \{I^{1,} I^{2},\ldots,I^{m}\}$. Each frame $I^t \in \mathbf{I}$ has similar structure and is represented by a three-tuple $\{A^t, Z^t, S^t\}$ where A^t is the set of initiatives to be prioritized; Z^t is the set of criteria for evaluating and prioritizing the initiatives; and S^t is the set of scenarios. Each frame at time t of scenario based preference models, denoted, I^t, produces output O^t which includes robustness measures for each initiative in A^t and the metrics for the influence for each scenario in S^t as chosen by one or more methods discussed in 3.4.

For each frame I^{t+1} the elements $\{A^{t+1}, Z^{t+1}, S^{t+1}\}$ are influenced by the inputs and outputs of frame I^t. There are several ways to perform iterative reframing analysis. In an initiative-focused frame, stakeholders select a subset of initiatives that are robust as defined by one or more metrics outlined in Task 2. Stakeholders may want to eliminate initiatives that are dominated with respect to scenarios frame t+1. An initiative a_1 is dominated if there exists $a_i \in A$ such that $V_j(a_1) \leq V_j(a_i)$ for all j = 0,…J. A robust initiative, (see Section 3.4) however, may be dominated, thus, stakeholders may select non-dominated initiatives along with initiatives with the highly robust initiatives for subsequent frames. It may be possible to combine different aspects of two or more initiatives to form a new initiative superior to any of its constituents (Frey et al., 2009). A new initiative might be imagined that is complementary in the sense that it has strengths in just those areas where the previous initiatives were less prioritized. In a scenario-focused frame, stakeholders may select a subset of influential scenarios for the next iteration. These influential scenarios can be identified according to the definitions outlined in Section 3.4. The subsequent frame may focus on more detailed descriptions of the emergent factors that are represented by the scenario. In a combination of initiative focused and scenario-focused frame, stakeholders may select a subset of robust initiatives and influential scenario to perform the frame t +1 of scenario-based preference analysis.

The following set of questions is recommended to aid in the reframing process:

1. Which scenarios are most influential in terms of reprioritizing initiatives?
    - *Describe the influential scenarios as more detailed scenarios. Identify whether their exists hidden criteria not yet captured. Are there alternative metrics for establishing success for a particular objective that might be considered under the new set of scenarios? The next frame t+1 may have a new set of Z^{t+1} of criteria and a new set S^{t+1} of scenarios.*
2. Which scenarios are threats to near-robust initiatives?
    - *Identify which criteria are driving the performance of these initiatives in given scenario and use this information to innovate/improve individual initiatives or search for combination with other initiatives (i.e. create initiative portfolios) that do well under given scenarios. The next frame t+1 could include as initiatives these improved initiatives (a) or various portfolios (b) as the set of initiatives A^{t+1} for prioritization.*
3. Which scenarios are opportunities to less prioritized initiatives?
    - *Identify which criteria are driving the performance of that initiative in*

given scenario and use this information to innovate/improve individual initiatives and/or search for combination with other initiatives (i.e. create initiative portfolios) that do well under given scenarios. The next frame t+1 could include as initiatives these improved initiatives (a) or various portfolios (b) as the set of initiatives A^{t+1} for prioritization.

4. Which initiatives are robust or near-robust to scenarios?
   - *Create more detailed design of robust initiatives. Are there new or additional criteria that are needed to further distinguish these initiatives? The next frame t+1 may have a new set A^{t+1} of initiatives, along with a new set Z^{t+1} of criteria and a new set S^{t+1} of scenarios.*
5. Are there missing scenarios, criteria, or initiatives?
   - *Reflect on the criteria and ask whether there are additional scenarios that would change the criteria preferences. Are there additional initiatives that would perform better under these new scenarios?*

In systems engineering, traceability is often emphasized. Capturing the intermediate outputs and reframing decisions between iterations is useful for documenting the evolution of the decision making rationale. Table 0-1 provides an example of how to capture, for each frame, the input, output, responses to the reframing questions and reframing decisions.

Table 0-1: Reporting of criteria, initiatives, scenarios, intermediate output and reframing -- scenario-based preferences for risk analysis in multiple time frames

Frame	Input	Output	Reframing Questions	Reframing
I^t	Initiatives $\{A^t\}$	Robust initiatives	Can any of the initiatives be combined/redesigned?	Initiatives eliminated Initiatives maintained New Initiatives
	Criteria $\{Z^t\}$		Are there new criteria as a result of new initiatives or new scenarios?	Criteria eliminated Criteria maintained New criteria
	Scenarios $\{S^t\}$	Influential scenarios	Are there more details of the scenarios to explore? Are there new scenarios as a result of the revised set of initiatives?	Scenarios eliminated Scenarios maintained New scenarios

The process should continue until the decision makers agree that the current model is not likely to change much in a future iteration and is considered *requisite*. A model can be considered requisite when no new intuitions arise from the group of decision makers (Phillips, 1984). According to Phillips, "at this point unease about the model has largely disappeared and the dialectic in the group has ceased. It is then possible to summarize the shared understanding of the group and gain commitment to the next steps". In practice, this means that the decision makers are satisfied with the model, the process can be paused and they can proceed on their own to reach a final decision.

For iterative scenario-based preference modeling, the exploration of initiatives, criteria, and scenarios must simultaneously be considered requisite, along with the initiative assessment and value preference information. If there are (i) no new scenarios that can be envisioned that change any of the value functions, (ii) no new initiatives that can be added to the initiative space, and (iii) no new criteria that can be used to further distinguish robust or non-dominated initiatives, then the model can be considered requisite. Essentially, it represents the key tradeoffs of initiatives across criteria and scenarios.

Figure 0-1 summarizes scenario-based preference analysis in multiple time frames. The process is initiated with identification of elements of the sets of initiatives, criteria, and scenarios and the development of a baseline multicriteria analysis model. The baseline multicriteria analysis is supplemented with the set of scenarios to create a scenario-based preference model. The outputs of this model are quantitative and qualitative observations of robust initiatives and influential scenarios. The outputs are combined with the reframing questions to come up with a revised set of initiatives, criteria, and scenarios. This scenario-based multi-criteria modeling process is then reinitiated. The overall process can be paused once no new initiatives, criteria, or scenarios are identified.

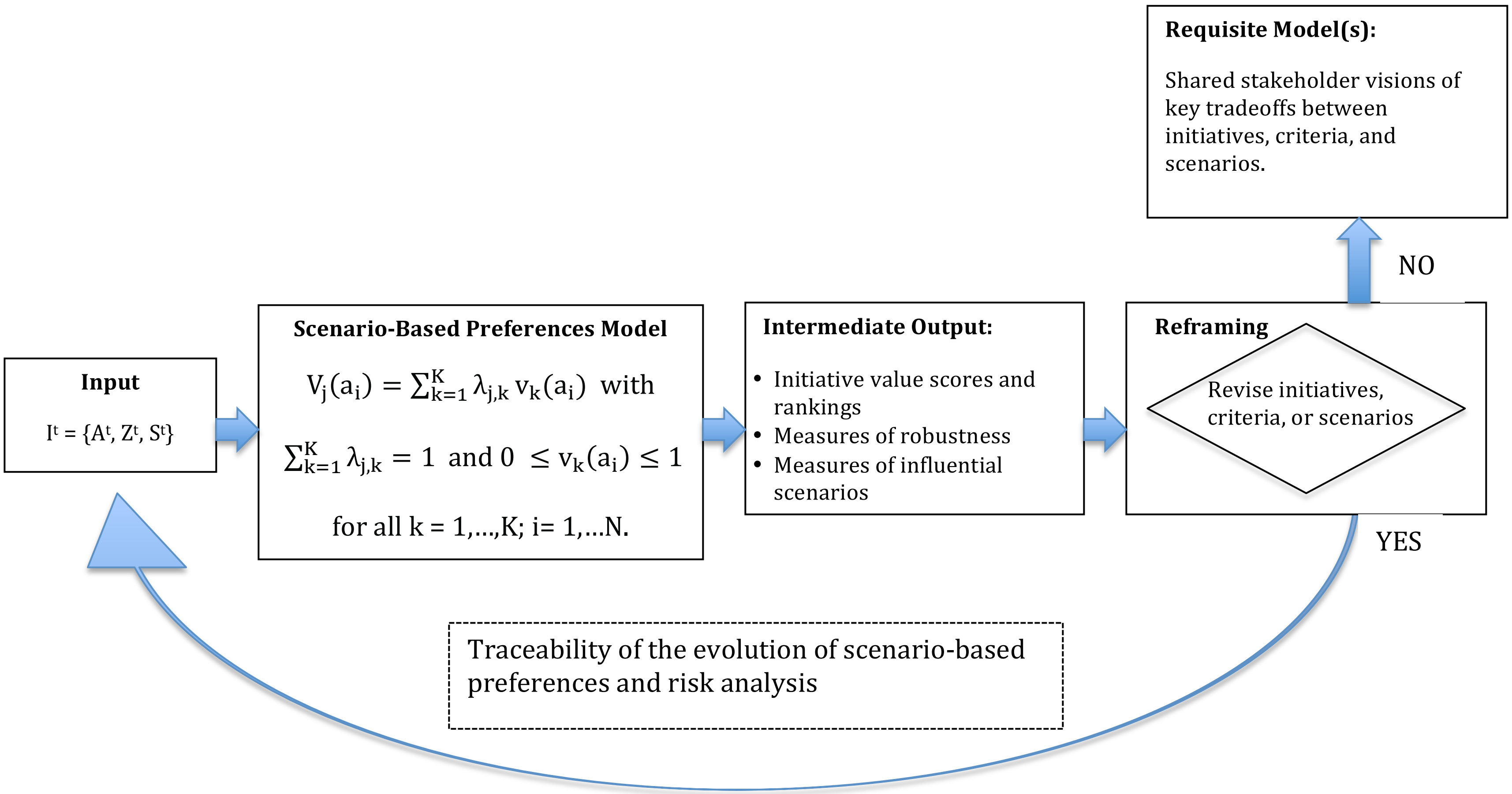

Figure 0-1: Summary-- concept for scenario-based preferences in multiple time frames.

3.6 Stakeholder Engagement and Traceability

This section provides recommendations for the expert engagement in order to implement the methods supporting scenario analysis in multiple time frames.

It is recommended that the methods be implemented in a facilitated manner. Phillips (2007) provides a review of decision conferencing and facilitation skills. The facilitator(s) should be familiar with multicriteria analysis and scenario-based preference modeling. Before the initial stakeholder meeting, it would be useful and time-saving for the analyst to prepare a survey to elicit an initial list of the initiatives and high-level objectives and possible key external uncertainties that can stimulate the formation of scenarios. It is helpful if the analyst can provide an example of a scenario to the stakeholders. A survey could ask the stakeholders the following questions prior to the initial meeting in order to ascertain a general understating of how stakeholder agree and disagree, and how a baseline value function can be built:

- Describe the scope of the current decision problem.
- Describe the high-level objectives for this decision
- Describe some criteria that could be used to evaluate initiatives
- Describe initiatives that could address the criteria
- Describe why each initiative might be a good one to select
- Describe any external elements that would change which initiative you prefer
- Describe any external elements that would change which criteria you would

emphasis to evaluate initiatives

. Describe the parties that are affected by the decision, even if these parties are not directly involved in the decision making. Would they value any of the criteria differently?

Next, the analyst should organize a meeting for the stakeholders to meet to discuss the problem as a group. First, the analyst should summarize the survey to the stakeholders and point out areas where they agreed and disagreed. The analyst can work with the stakeholders to create a list of criteria to measure achievement of objectives as derived from the survey. The stakeholders should then discuss and finalize a list of criteria to measure the achievement of each objective. The set of properties of the criteria set should be complete and non-redundant (Keeney, 2007, Keeney and Raffia 1976). According to Keeney and Raiffia (1976) the set of criteria should be a "sufficiently rich and meaningful set of descriptors to capture the essence of the problem". More details on constructing a good set of criteria can be found in Raiffia (1976), Keeney and Raiffa (1993), von Winterfeldt and Edwards (1986) and Keeney (1992).

Once a set of criteria are chosen, the stakeholders should discuss in a group setting the assumptions about the internal and external environment that are being used to evaluate each initiative on each criterion, $v_k(z_i^k)$, and to evaluate criteria preferences, $\lambda_k \in \{ \lambda_1, \dots, \lambda_k\}$. For example, one assumption might be that the price of fuel and electricity continues to grow at historical rates. Next, multicriteria analysis assumptions can be used to build a baseline value function as described earlier in this chapter. Additional details on how to construct the baseline preference model can be found in Chapter 7 of Karvetski (2011d) as well as in Keeney and Raffia (1993). The results of the baseline model can be discussed and any discrepancies with stakeholder intuitions can be discussed and used to refine the baseline model.

Next, the stakeholders are asked to identify externalities that would change any $v_k(z_i^k)$ or any $\lambda_k \in \{\lambda_1, \ldots, \lambda_k\}$. One way of identifying scenarios is to ask why the stakeholders had difficulties in providing preference information for the coefficients in the baseline scenario $\lambda_k \in \{\lambda_1, \ldots, \lambda_k\}$. Usually it is helpful if the analyst can identify a scenario from background research, the initial survey, or the stakeholder discussion that can be used as an example to the group. Once several scenarios are identified and evaluated according the methods described in Section 3.2, the stakeholders should look at the scenario-based results and again discuss any discrepancies with the stakeholder intuitions.

Before initiating the subsequent frame of scenario-based preference model, the stakeholders should be given time to reflect on the intermediate outputs. Perhaps, this need be only several hours, but perhaps it could be several days or weeks. The stakeholders will need time to think about the reframing questions presented in Section 3.5 in order to reframe the decision problem. They may need time to do some background research to identify new scenarios and to design new initiatives. Also, perhaps the current set of stakeholders is not adequate for the next frame and additional experts may need to be recruited for participation. After an appropriate time of reflection has passed, the stakeholders can reconvene to create a new model.

At this point, they should have a better appreciation for how to revise the initiative, criteria, and scenarios. This process of engagement-reflection-reengagement should continue until the stakeholders feel that that model is requisite as described in Section 3.6. Further research on stakeholder engagement is recommended as an area of future research.

A software tool has been developed to support the scenario-based preference analysis as described in Appendix A.

3.7 Chapter Summary

This chapter discussed the methods of scenario-based preference modeling in risk analysis across multiple time frames. Section 3.2 described a scenario-based multicriteria decision analysis model to prioritize a set of initiatives under several uncertain futures that are represented as scenarios. The next two sections described how to interpret the output of the scenario-based preference model that is useful for systems engineering and risk analysis. Section 3.3 discussed the metrics which can be used to measure the robustness of initiatives. Section 3.4 discussed the metrics with can be used to measure the influence of scenarios. Section 3.5 discussed scenario-based preference models in multiple time frames. It discussed how the output described in Section 3.3 and 3.4 can be used to updating subsequent analyses. Section 3.6 discussed the practical implementation of engaging stakeholders in the iterative process. Chapter 4 and Chapter 5 will provide case studies to demonstrate the methods.

Case Study - Energy Security for Installations

4.1 Chapter Overview

This chapter describes a case study of scenario-based preferences in multiple time frames for risk analysis of energy system initiatives for military installations. The chapter begins with a background on energy security decision-making at military installations. Next, two previous frames of scenario-based preference analysis are discussed. Then two additional frames are demonstrated in detail and future frames are suggested from the results of all previous frames. Finally, a discussion of the results of the overall iterative process is presented. The scenarios of concern can be comprised of a variety of emergent and future conditions throughout the system lifecycle. The case study follows the methods explained in Chapter 3, and describes the usefulness of the methods for supporting identification of influential scenarios in multiple time frames.

4.2 Background

Assuring energy availability and reliability for military installations against outages or disruptions of the electrical grid is important for economic competitiveness, mission, and national security. The 2008 Defense Science Board describes that "critical national security and Homeland defense missions are at an unacceptably high risk of extended outage from failure of the grid." Dependence on commercially owned, aging electrical grid infrastructure is a key challenge of the coming decades, and the military among others is supporting research and development initiatives that can help to assure that energy supply meets critical demand at multiple time and spatial scales. In particular, energy managers for military installations need a rationale for selecting among innovative technologies and methodologies for energy quality and quantity in support of their critical missions. Energy managers must consider various strategic objectives, including: reducing consumption, increasing efficiency, reducing dependence on fossil fuels, judicious use of renewable resources, and reducing adverse impacts to the environment. Stakeholders of energy investments in particular are faced with complex challenges, where uncertainties can span technology, environment, regulatory, socio-demographic, political, economic, and other factors. Emergent and future conditions, to the extent they can be known or predicted, should influence the priorities for research and development portfolios. Changing federal, state, and local regulations such as carbon taxes, renewable portfolio standards, and utility tariff regulations will significantly influence the financial feasibility of various innovative technologies. The volatility in supplies and demands of fossil fuels will affect availability and market prices of a variety of energy resources. Regulatory and political changes are an important class of emergent conditions. Emergent conditions from this class include new energy guidelines and incentives. International conditions include shifts in the geopolitical power relating to different fuel and rare earth resources. Conditions at the installation that can impact mission execution include local disruption of energy services caused by commercial energy grid failures, destruction of energy systems or terrorism, and deterioration of other interconnected infrastructures. Other conditions involve weather and climate, fuel and material supply chains, institutional and organizational issues, and changing security requirements. The identification of emergent and future conditions (as scenarios) motivates energy managers and stakeholders to think holistically to identify a comprehensive set of concerns for strategic planning.

Energy research and development decisions have multiple stakeholders including utilities, users/customers, technology vendors, system owners, and others. The stakeholders have different perspectives and experience, including varying degrees of knowledge of emergent and future conditions that should be considered.

The objective of this case study is to identify and address uncertainties of energy infrastructure as an essential influence to *priority-setting* among initiatives, rather than in a stand-alone *risk* or *opportunities* assessment. The dissertation extends previous work on energy security and emergent conditions for infrastructure systems (Hamilton, 2013a; Karvetski et al., 2011a, 2011b, 2011c, 2010, 2009; Lambert et al., 2011a, 2011b, 2011c, 2010; Martinez et al., 2011, 2010, Martinez and Lambert, 2010; Joshi and Lambert 2011).

4.3 Past Time Frames of Analysis

4.3.1 Overview

Several frames of scenario-based preference models were previously developed and published during the period of 2009-2012. During this period (2009-2011), researchers (including the author) from the Center for Risk Management of Engineering Systems at the University of Virginia were members of the Fort Belvoir Energy Security Working Group. UVA worked with stakeholders at Fort Belvoir to develop and test an energy security assessment software tool. The tool and reports can be viewed at http://www.virginia.edu/crmes/energysecurity/energy. The UVA workbook supported energy system decision-making at Fort, Belvoir, Virginia.

4.3.2 First Frame - Conceptual Design Priorities for an Installation

The first frame (I^1) – *conceptual design priorities for an installation* – is concerned with energy system priority setting from the perspective of an individual installation. This frame is described in Karvetski and Lambert (2012) and is used as the starting point for the multiple time frame analysis.

During the period 2009-2011 the Fort Belvoir Energy Working Group was considering conceptual designs for improving energy security in the Area 300 Compound. This compound consists of forty-six buildings requiring approximately four megawatts (MW) of power. Within the compound, there are several scientific laboratories that are often running multi-week experiments on high technology equipment. Currently, the installation receives its electricity from a large utility provider. It uses electricity for its cooling needs via electric coolers. The heating needs are met mainly through a natural gas steam plant, which is aged and requires frequent maintenance each year. The installation experiences many outages a year, often due to weather, trees falling, and animals. Recently, the installation experienced over forty hours of outages in a single year. This poses a problem to the entire installation and particularly for the research and scientific laboratories. Whenever the power is lost or intermittent, these laboratories can lose days or weeks of work and data collection, and the experiment often has to be reinitiated. Importantly, the humidity, temperature, and air quality of the laboratories must be kept strictly regulated, and any power outage can cause contamination of materials and equipment. Currently, the utility supplied power is not of consistent quality, and these variations in voltages cause a problem for some of the electronic equipment. Thus, the installation is investigating multiple diverse initiatives to address the operational need for consistent, reliable, and quality electricity.

Six conceptual initiatives were evaluated against seven criteria and five scenarios representing stakeholder concerns. The initiatives six initiatives were:

- a_1: do nothing
- a_2: bury the power lines
- a_3: microturbine-A (1 MW of natural gas microturbines to support five buildings)
- a_4: microturbine-B (4 MW of natural gas microturbines to support additional buildings and remove the existing natural gas steam plant)
- a_5: backup generators (standalone/dedicated generators)
- a_6: reconfiguration of lines, switches, breaks
- a_7: microgrid of backup generators

The criteria were derived from stakeholder input and the following guidance documents and the Energy Policy Act of 2005, Energy Independence and Security Act 2007, Executive Order 13423 , Department of Defense 4170.11, Army Regulation 420-1, Army Energy and Water Campaign Plan, and Army Energy Security Implementation Strategy (AESIS, 2009).

The seven criteria for evaluating initiatives included:

- z_1 quality prime or interrupted power for the five buildings
- z_2 reduce cost
- z_3 procure funding
- z_4 reduce environmental impact
- z_5 conform to organizational aims of the government
- z_6 provide innovation and serving as a test-bed or proof-of-principle
- z_7 reducing vulnerability of the system to threats

The criteria value functions and baseline set of coefficients are provided in Appendix B.

Five scenarios representing stakeholder concerns include the following (see Karvetski et al. 2012):

1. s_1 Cyber: the increased potential of a cyber-attacks to any part of the energy distribution system
2. s_2 Natural disaster: the occurrence of a natural disaster in the region of the installation

3. s_3 Human error, disgruntled employee: the increased potential of disruption of the service caused by human error or intentional attack by employee on installation or utility company
4. s_4_ Terrorist attack: increased potential for terrorist attack in the region of the installation
5. s_5 International economic fear: the increasing anxiety of a bleak economic future.

The results of this first frame are documented in Karvetski et al. 2012 and are summarized below in Table 0-1. The results showed the top initiative was not changed much by the scenario analysis. The top prioritized initiative was microturbine-B which was onsite gas-fired microturbine that included trigeneration (electricity, cooling, and heating) sized for base load of the entire 46 buildings of the complex. This initiative remained in the top priority for all scenarios. The only scenario to change the prioritization was international economic fear. This changed onsite gas fuel from second in priority to third and backup diesel generator became higher. Also, the results show that the initiative microturbine-A and microgrid alternate for second and third priority under the various scenarios. This indicates that there may be some advantage to combining elements of the design for each of these initiatives in a subsequent time frame.

Table 0-1*: Conceptual design time frame* - value scores of six initiatives and corresponding ranking (in parentheses) across each scenario (across each row) (from Karvetski and Lambert, 2012).

	a_1 no action	a_2 bury lines	a_3 microturbine-A	a_4 microturbine-B	a_5 backup generators	a_6 reconfiguration of lines, switches, breaks	a_7 microgrid
baseline	0 (7th)	23 (6th)	85 (2nd)	**86 (1st)**	45 (4th)	40 (5th)	77 (3rd)
s_1 cyber	0 (7th)	26 (6th)	81 (3rd)	**84 (1st)**	45 (4th)	37 (5th)	82 (2nd)
s_2 natural disaster	0 (7th)	28 (6th)	86 (2nd)	**87 (1st)**	47 (4th)	41 (5th)	81 (2nd)
s_3 human error, disgruntled employee	0 (7th)	27 (6th)	83 (3rd)	**86 (1st)**	44 (4th)	36 (5th)	84 (2nd)
s_4 terrorist	0 (7th)	28 (6th)	86 (2nd)	**87 (1st)**	47 (4th)	41 (5th)	81 (3rd)
s_5 international economic fear	0 (7th)	22 (6th)	**87 (1st)**	77 (2nd)	39 (5th)	48 (4th)	72 (3rd)

4.3.3 Second Frame – R&D Priorities across Installations

The first time frame prioritized conceptual energy security designs for an individual installation. It is important to realize that the decisions made at individual installations are a part of a larger overall strategy for energy security across installations. The second frame (I^2) – *R&D priorities across installations* - takes a strategic approach to the problem. This frame is documented in Hamilton et al. (2013a). The second frame (I^2) prioritizes six research & development (R&D) initiatives that are representative of those considered for funding in the Department of Defense's Environmental Security Technology Certification Program (ESTCP). They six initiatives are listed Table 0-2 and include microgrids, solar cogeneration with battery backup, geothermal with cognitive building management, microturbines and fuel cells, innovative heating ventilation and cooling (HVAC), and electric vehicles with optimization. Ten criteria listed in Table 0-3 were used to evaluate the initiatives including: reduce operation and maintenance costs, increase self-sufficiency, reduce energy consumption, reduce foreign energy inputs, reduce carbon emissions, increase energy efficiency, increase renewable energy, reduce dependency on foreign rare earths, reduce cyber-attack vulnerability, and increase technology innovation/spillover. The criteria were given equal weight for the baseline scenarios. Table 0-4 provides a Likert scale assessment of each initiative on each criteria.

Table 0-2: *R&D priorities time frame* - description of six R&D initiatives selected for prioritization

R&D Initiatives	Description
a_1 Microgrids with integrated control	Including integrated monitoring and control & automated demand response, and energy usage and cost real time visualization
a_2 Solar cogeneration with battery	Combination of solar PV and solar hot water (SHW) technologies into a single integrated solar cogeneration system with sodium-metal-halide battery energy storage
a_3 Geothermal with cognitive building management	Geothermal heat pumps for heating, cooling, and hot water with cognitive energy management system that optimizes building energy usage based on intelligent occupancy-based building automation strategies.
a_4 Microturbines & fuel cells with cogeneration	Microturbines and stationary fuel cells for distributed generation as prime power including cogeneration of electricity and thermal energy
a_5 Innovative HVAC and dynamic windows	Advanced dedicated outside air system that incorporates nanotechnology membrane to efficiently control humidity separately from temperature and dynamic windows that switch from a tinted to clear state to optimize solar heat gain and day lighting.
a_5 Electric vehicle fleet with optimization	Non-tactical electric fleet including fleet management and optimization tool to schedule charging and discharging of electric vehicles

Table 0-3:*R&D priorities time frame* - criteria and criteria coefficients (shown as a percentage)

Criteria	Baseline Coefficient (percentage)
z_1 Reduce O&M costs	10%
z_2 Increase self sufficiency	10%
z_3 Reduce energy consumption	10%
z_4 Reduce foreign energy inputs	10%
z_5 Reduce carbon emissions	10%
z_6 Increase energy efficiency	10%
z_7 Increase renewable energy	10%
z_8 Reduce dependency on foreign rare earths	10%
z_9 Reduce cyber attack vulnerability	10%
z_{10} Increase technology innovation/spillover	10%

Table 0-4: *R&D priorities time frame* - Likert type assessment of the R&D initiatives for each of the performance criteria.

	a_1 Microgrids with integrated control	a_2 Solar cogeneration with battery backup	a_3 Geothermal with cognitive building management	a_4 Microturbines and fuel cells with cogeneration	a_5 Innovative HVAC and dynamic windows	a_6 Electric fleet vehicles with optimization
$z_{1.}$ Reduce O&M costs	1	0.67	0.67	0.33	0.67	0.33
$z_{2.}$ Increase self-sufficiency	1	0.33	0.67	1	0.33	0
$z_{3.}$ Reduce energy consumption	1	0	0.67	0	0.67	1
$z_{4.}$ Reduce foreign energy	0.33	1	1	0.67	0.33	1
$z_{5.}$ Reduce carbon emissions	1	1	0.67	0.67	0.67	1
$z_{6.}$ Increase energy efficiency	1	0.33	0.67	0.67	0.33	0.67
$z_{7.}$ Increase renewable energy	0	1	1	0	0	0.67
$z_{8.}$ Reduce foreign rare earths	0.33	0	0.33	0	0.33	0
$z_{9.}$ Reduce cyber vulnerability	0	0.33	0.33	0.33	0.33	0
$z_{10.}$ Increase technology innovation	1	0.67	0.67	0.33	0.67	1

Five scenarios were developed which represent different stakeholders whose views or advocacy positions with regards energy security have been influenced by their knowledge base, experience and concern for combinations of future emergent conditions. The first scenario, s_1, is a *Green Movement* perspective. In this scenario, the stakeholder is most concerned with reducing the environmental impacts of energy usage and complying with environmental regulations. Examples of emergent conditions that this stakeholder may be concerned about include stricter federal renewable energy requirements, the development of a national renewable portfolio standard, and carbon tax/legislation. The second scenario, s_2, is a *National Security* perspective. This stakeholder is primarily concerned with reducing dependence on foreign countries and reducing vulnerability to cyber-attacks. Some emergent conditions that this stakeholder may be concerned about include conflict in oil-producing countries, conflict in countries with significant rare earth resources needed for renewable and alternative energy technologies, and cyber-attacks to energy infrastructure. The third scenario, s_3, is an *Islanding* perspective. In this perspective, the stakeholder is primarily concerned with the ability to "island" the installation and provide sufficient energy resources to support critical missions. An emergent condition that this stakeholder may be concerned with is the deterioration and vulnerability of commercial power grid infrastructure and the ability to protect critical missions. The fourth scenario, s_4, is a *Technology Innovation* perspective where the stakeholder is concerned with investing in R&D technologies and systems that have the greatest potential for widespread adoption in industry, business, and residential situations. Some emergent conditions that this stakeholder may be concerned about include lack of private investment in R&D and increased pressure for the government to provide proof-of-principle. The fifth scenario, s_5, is a *Cost* perspective where the stakeholder is concerned with lowering the long term operating and maintenance costs of energy systems and mitigating risks of variable prices in fossil fuel sources. Some emergent conditions that this stakeholder may be concerned about include slow economic development, cutbacks in government spending, and volatility of price of fossil fuels.

These scenarios were used to reassess the baseline criteria preferences or weights under each scenario. The criteria coefficients are adjusted relative to each other (normalizing or dividing each by a constant still maintains the same preference information) (Karvetski and Lambert, 2012). These adjustments answer the following question: "Compared to a baseline scenario, which of the criteria becomes more important or less important under scenario s_k?" The answer to the question is categorized as a major decrease in importance, minor decrease in importance, minor increase in importance, or major increase in importance. Table 0-5 provides the reassessment of the preferences for the criteria in each scenario.

If λ_k increases under scenario s_j compared to the baseline scenario, the coefficient of this criterion is adjusted through defining a constant $\alpha > 1$ and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k^{th} criterion is then

$$\lambda'_k = \alpha \times \lambda_k.$$

The set of constant multipliers are defined for this case study are {1/9, 1/3, 1, 3,9}, where a major decrease corresponds to a multiplier of 1/9, a minor decrease corresponds to a multiplier of 1/3, no change corresponds to a multiplier of 1, a minor increase corresponds to a multiplier of 3 and a major increase corresponds to a multiplier of 9. The new set of λ_k' are then normalized to sum to one. Table 0-6 displays how the baseline criteria coefficients are adjusted.

For example in the scenario s_1 Green Movement:

$$\lambda_{1,1}{}' = 0.1 \times 1/3 = 0.033$$
$$\lambda_{1,2}{}' = 0.1 \times 1 = 0.1$$
$$\lambda_{1,3}{}' = 0.1 \times 9 = \ 0.9$$
$$\lambda_{1.4}{}' = 0.1 \times 1 = 0.1$$
$$\lambda_{1,5}{}' = 0.1 \times 9 = 0.9$$
$$\lambda_{1,6}{}' = 0.1 \times 9 = 0.9$$
$$\lambda_{1,7}{}' = 0.1 \times 9 = 0.9$$
$$\lambda_{1,8}{}' = 0.1 \times 1 = 0.1$$
$$\lambda_{1,9}{}' = 0.1 \times 1 = 0.1$$
$$\lambda_{1,10}{}' = 0.1 \times 1 = 0.1$$

Normalization so that the criteria coefficients sum to one yields:

$$\lambda_{1,1} = 0.0081$$
$$\lambda_{1,2} = 0.0242$$
$$\lambda_{1,3} = 0.2177$$
$$\lambda_{1,4} = 0.0242$$
$$\lambda_{1,5} = 0.2177$$
$$\lambda_{1,6} = 0.2177$$
$$\lambda_{1,7} = 0.2177$$
$$\lambda_{1,8} = 0.0242$$
$$\lambda_{1,9} = 0.0242$$
$$\lambda_{1,10} = 0.0242$$

The same process is applied for the other four scenarios. Table 0-6 displays the associated normalized adjustments in the criteria coefficients given the responses in Table 0-5. These criteria coefficients were then used with the value scores of Table 0-4 to produce a value score for each initiative under each scenario using the equation:

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{ with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

for all k = 1,…,K; i= 1,…N

Table 0-5: *R&D Priorities time frame* - elicitation of incremental adjustments to the priorities among criteria across the five scenarios.

	s_1 Green Movement	s_2 National Security	s_3 Islanding	s_4 Technology Innovation	s_5 Economic Perspective
z_1. Reduce O&M costs	minor decrease	minor increase	minor decrease		MAJOR INCREASE
z_2. Increase self-sufficiency			MAJOR INCREASE		
z_3. Reduce energy consumption	MAJOR INCREASE				MAJOR INCREASE
z_4. Reduce foreign energy		MAJOR INCREASE			
z_5. Reduce carbon emissions	MAJOR INCREASE				
z_6. Increase energy efficiency	MAJOR INCREASE				MAJOR INCREASE
z_7. Increase renewable energy	MAJOR INCREASE				
z_8. Reduce foreign rare earths		MAJOR INCREASE			
z_9. Reduce cyber vulnerability		MAJOR INCREASE			
z_{10}. Increase technology innovation				MAJOR INCREASE	

Table 0-6: *R&D priorities time frame* - corresponding normalized adjusted criteria coefficient expressed as a percentage for each criterion in each scenario (including baseline)

	Baseline	s_1 Green Movement	s_2 National Security	s_3 Islanding	s_4 Technology Innovation	s_5 Economic Perspective
z_1. Reduce O&M costs	10.00%	0.81%	8.33%	1.92%	5.56%	26.47%
z_2. Increase self-sufficiency	10.00%	2.42%	2.78%	51.92%	5.56%	2.94%
z_3. Reduce energy consumption	10.00%	21.77%	2.78%	5.77%	5.56%	26.47%
z_4. Reduce foreign energy	10.00%	2.42%	25.00%	5.77%	5.56%	2.94%
z_5. Reduce carbon emissions	10.00%	21.77%	2.78%	5.77%	5.56%	2.94%
z_6. Increase energy efficiency	10.00%	21.77%	2.78%	5.77%	5.56%	26.47%
z_7. Increase renewable energy	10.00%	21.77%	2.78%	5.77%	5.56%	2.94%
z_8. Reduce foreign rare earths	10.00%	2.42%	25.00%	5.77%	5.56%	2.94%
z_9. Reduce cyber vulnerability	10.00%	2.42%	25.00%	5.77%	5.56%	2.94%
z_{10}. Increase technology innovation	10.00%	2.42%	2.78%	5.77%	50.00%	2.94%

Table 0-7 shows the output from the R&D priorities time frame. The table describes the R&D initiatives ranked across the baseline and five scenarios described above, along with the numeric value added prioritization scores. For example, the initiative, a_1, *Microgrids with integrated control* and a_3, *Geothermal with cognitive building management* are ranked as first priority under the baseline assessment with value added scores of sixty-seven. Under the scenario, s_2, *National Security,* the initiative, a_1, *Microgrids with integrated control,* drops to fourth with a value added score of thirty-nine.

Table 0-8 describes the robust R&D initiatives, nearly robust R&D initiatives, influential scenarios, scenarios that reduce initiatives in priority, scenarios that rise initiatives in priority, R&D initiatives that fall in priority relative to the baseline scenario, and R&D initiatives that rise in priority relative to the baseline scenario.

In the baseline assessment, the top-ranked initiatives are the, a_1, *Microgrid with integrated control* and, a_3, *Geothermal with cognitive building management*. The initiative, a_3, *Geothermal with cognitive building management* can be considered robust since its priority remains in the top three for all scenarios. The initiative, a_1, *Microgrid with integrated control* can be considered fairly robust. It is highly prioritized in all but one scenario, *National Security,* where the fear of increased vulnerability to cyber-attacks causes this option to be less desirable. The stakeholders could also compare the initiative, a_1, *Microgrid with integrated control* to a_3, *Geothermal with cognitive building management* to design a new R&D initiative that would be more robust and responsive to all scenarios.

The most influential scenario is s_3, *Islanding.* This is based on scores for each combination of conditions representing the sum of square ranking (SSRC) changes of the ranking values in comparison to the baseline ranking. Under this scenario, a_4, *Microturbines and fuel cells with cogeneration* becomes more highly prioritized, due to its ability to provide all heating, cooling, and electricity needs. The initiative, a_6, *Electric vehicles fleet with optimization* becomes much lower in priority under the s_3, *Islanding,* scenario. This is due to the increased dependence on the private utility grid to support the energy required to maintain the fleet.

Scenarios that create the most negative change in rankings include s_3, *Islanding* and s_2, *National Security*. Under *Islanding*, the initiative, a_6, *Electric vehicles fleet with optimization* drops from ranked third to sixth. *National security* causes microgrids to drop from ranked first to fourth. The scenario presenting the most opportunity is *Islanding* because it creates the most positive changes in rankings. Under *Islanding*, the initiative, a_1, *Microturbines and fuel cells with cogeneration* increase from ranked sixth to second.

Initiatives with downside-priority (risk) include, a_6, *Electric vehicle fleet with optimization* and, a_1, *Microgrids with integrated control*. The initiative, a_6, *Electric vehicle fleet with optimization* is ranked third in the baseline scenario and highly in many other scenarios, however, it is ranked sixth in the *Islanding* scenario. The initiative, a_1 *Microgrids with integrated control* is ranked highly in all scenarios except *National Security*, where it is ranked fourth.

An R&D initiative with upside-priority (opportunity) is, a_4 *Microturbines & fuel cells with cogeneration*. This initiative is not highly ranked in the baseline scenario but it became more highly prioritized under the *Islanding* scenario.

Table 0-7: *R&D priorities time frame* - value scores of six initiatives and corresponding ranking (in parentheses) across each scenario (across each row)

	a_1 Microgirds with integrated control	a_2 Solar cogeneration with battery	a_3 Geothermal with cognitive building management	a_4 Microturbines & fuel cells with cogeneration	a_5 Innovative HVAC and dynamic windows	a_6 Electric vehicle fleet with optimization
baseline	**67 (1st)**	53 (4th)	**67 (1st)**	40 (6th)	43 (5th)	57 (3rd)
s_1 Green movement	73 (3rd)	57(2nd)	73 (2nd)	35 (6th)	42 (5th)	**78 (1st)**
s_2 National Security	39 (4th)	48 (4th)	**59 (1st)**	35 (6th)	38 (5th)	40 (3rd)
s_3 Islanding	**81 (1st)**	44 (4th)	67 (3rd)	68 (2nd)	38 (5th)	31 (6th)
s_4 Technology Innovation	**81 (1st)**	59 (4th)	67 (3rd)	37(6th)	54 (5th)	76 (2nd)
s_5 Economic Perspective	**90 (1st)**	39 (5th)	67 (2nd)	35 (6th)	52 (4th)	64 (3rd)

Table 0-8: *R&D priorities time frame* - summary of key intermediate results of the scenario analysis

Type of Result	Description
Robust R&D initiatives	***a_3* *Geothermal with cognitive building management*** is the most robust scenario. It is highly prioritized in the baseline scenario and remains in the top three for all scenarios
Nearly robust R&D initiatives	***a_1* *Microgrids with integrated control*** is a nearly robust scenario. It is highly prioritized in the baseline scenario and remains in the top three for all scenarios except *National Security* scenario
Influential scenarios of emergent and future conditions	***Islanding*** provide the most changes to prioritization of initiatives. This is based on scores for each combination of conditions representing the sum of square ranking (SSRC) changes of the ranking values in comparison to the baseline ranking. Under this scenario, a_4 *Microturbines and fuel cells with cogeneration* become much more prioritized, and a_6 *Electric vehicles fleet with optimization* becomes much less prioritized
Scenarios that reduce initiatives in priority	***Islanding*** **and** ***National Security*** creates the most negative changes in rankings. Under *Islanding,* a_6 *Electric vehicles fleet with optimization* drops from ranked third to sixth. *National security* causes microgrids to drop from ranked first to fourth.
Scenarios that raise initiatives in priority	***Islanding*** create the most positive changes in rankings. Under *Islanding*, a_1 *Microturbines and fuel cells with cogeneration* increase from ranked sixth to second.
R&D initiatives that fall in priority relative to the baseline scenario	The initiative **a_6 Electric vehicle fleet with optimization** ranked third in the baseline scenario and highly in many other scenarios, however, it is ranked sixth in the *Islanding* scenario. The initiative **a_1 Microgrids with integrated control** is ranked highly in all scenarios except *National Security*, where it is ranked fourth
R&D initiatives that rise in priority relative to the baseline scenario	The initiative **a_4 Microturbines & fuel cells with cogeneration** are not highly ranked in the baseline scenario but become much more desirable under the *Islanding* scenario

4.3.4 Reframing for Subsequent Time Frames

The results of the previous time frames can be used to revise the input into the next frames. From the first frame (I^1) - conceptual design priorities for an individual installation - both designs for distributed natural gas microturbines and microgrids were highly prioritized. The initiatives *a_2 bury lines, a_5 standalone backup generators, and a_6 reconfiguration of lines, switches, and breaks* are low priority in all scenarios, thus they are eliminated from further analysis. The scenario analysis showed little change in the ranking of initiatives across scenarios. After reflection, it was decided that the set of scenarios were not inclusive enough of various concerns of the stakeholders and/or were repetitive. The scenarios *s_1 cyber, s_2 natural disaster*, *s_3 human error*, *disgruntled employee* and *s_4 terrorist* have a very similar adjustment to the weight of the criteria. It was decided that these should be revised in to two more distinguishable scenarios.

The second frame (I^2) – R&D priorities – provides several revised scenarios that can be included in the next frame. The first revised scenario is an *islanding scenario,* which is mainly concerned with risks to the external electrical power system. The second revised scenario is a *cyber and terrorism* scenario, and in predominately concerned with intentional attacks to any part of the energy distribution system both on-site and off-site. The next frame will have a revised set of scenarios to perform scenario-based preference analysis. A new initiative, *solar photovoltaic (PV)* was identified for the next frame. The addition of this new initiative inspired the inclusion of the *green movement* scenario of the R&D frame (I^2) that focuses on renewable policies for the next frame. Also, none of the scenarios addressed a situation in which the criteria *provide proof-of principle* would become relatively more important. Thus the *technology innovation* scenario from the R&D frame was included to account for a situation in which this criterion would be more important. The new set of scenarios will be revisited in more detail in the next section. A summary of the input, output, reframing questions and reframing decisions is provided in Table 0-9.

Table 0-9: Reporting of criteria, initiatives, scenarios, intermediate output and reframing of scenario-based preference model for first time frame - conceptual design priorities for an installation

Input	Output	Reframing Questions	Reframing
Six initiatives *No action* *Bury lines* *Microturbine –A (critical load)* *Microturbine-B (base load)* *Standalone backup generators* *Reconfiguration of lines, switches, breaks* *Microgrid of backup generators*	**Three Robust initiatives** *Microturbine-A (critical load)* *Microturbine- B (base electrical load)* *Microgrid* *Backup generators*		**Three initiatives eliminated** *Bury lines* *Standalone backup generators* *Reconfiguration of lines, switches, breaks* **One new initiative** *Solar PV* **Four initiative maintained** *No action* *Microturbine-A (critical load)* *Microturbine- B (base electrical load)* *Microgrid of backup generators*
Seven Criteria *Reduced costs* *Quality, prime power for five buildings* *Achievement of governmental goals* *Provide proof-of-principle, lessons learned* *Procure funding* *Reduce physical/non-physical vulnerability* *Reduce environmental impact*		Elements of the criterion *maximize achievement of governmental goals* are redundant with *Maximize quality, prime power* and *Reduce environmental impact.*	**One revised criteria** *Maximize achievement of governmental goals* to be replaced with *maximize renewable energy*
Five Scenarios *Cyber* *Natural disaster* *Human error, disgruntled* *Terrorist* *International economic fear*	**One influential scenario** *International economic fear*	Several scenarios were revised to be more distinct. *Terrorist, Natural disaster, Cyber and human error, disgruntled employee disgruntled are revised in to two new scenarios (Islanding Cyber and terrorism)*	**Two revised scenarios** *Islanding* *Cyber and terrorism* **One scenario maintained** *International economic fear* **Two new scenarios** *Renewable policies* *Technology innovation*

4.4 Third Time Frame – Strategic Priorities for an Installation

4.4.1 Overview

The third time frame (I^3) – strategic priorities for an installation - is similar to I^1 in that it is priority setting from the perspective of an individual installation. However, this frame will incorporate scenarios inspired from consideration of the strategic level of the R&D frame (I^2). The frame will prioritize five initiatives using seven criteria under five scenarios of future emergent conditions. The frame will provide outputs that describe the robustness of each initiative and the influence or risk of each scenario. This frame (I^3) will also discuss the relationship of the input to the output of the previous frames (I^1 and I^2) and to the input of subsequent frames (I^4).

4.4.2 Baseline Analysis

In this frame, five initiatives were selected to be prioritized, which include the no-action alternative. Table 0-10 provides a description of these five energy initiatives selected for the set A. The initiatives range from investing in solar photovoltaic systems to natural gas powered microturbines with electricity, heating, and cooling abilities (trigeneration) to an electricity microgrid of existing diesel backup generators. The initiatives evaluated in the frame I^1 were updated in this model. Three initiatives from the previous frame were eliminated because they had a low ranking in all scenarios. An additional initiative, solar PV, was added to the analysis. The top three ranked initiatives were maintained in this frame because they were highly prioritized in all scenarios. These include both microturbine initiatives and the microgrid of existing backup generators. The no action initiative was maintained for this frame as well, although it was ranked very low in all scenarios. Table 0-11 provides seven performance criteria for the criteria set $Z=\{z_1,\ldots,z_m\}$. The criteria are similar to those as used in Karvetski and Lambert (2012) except that the criterion *maximize achievement of governmental goals* was replaced with *maximize renewable energy*. The motivation for this change is that the constructed scale used to measure the criterion *maximize achievement of governmental goals* was a function of reduced energy consumption, increased energy efficiency, increased renewable energy, and assured access to sufficient supply. After reflection, it was decided that the elements reduced energy consumption and increased energy efficiency are redundant with the criterion reduce environmental impact and the element assured access to sufficient supply is redundant with the criterion reduce physical/non-physical vulnerability. Thus, it was decided to use increase renewable/alternative energy as its own criterion. This criterion is measured in units of kwh/year of renewable/alternative energy.

The baseline set of criteria coefficients were assessed using swing-weighting technique. The criterion, Z^1 was deemed the most important. The relative worth ratios were then assessed answering the question: Given the criterion Z^1 and $Z^{y,}$ what is the relative worth of exchanging z^{1o} for z^{1*} compared to exchanging z^{yo} for z^{y*}. The worth ratio for Z^1 is set to $w_1 = 1$. The worth ratios were assess as follows: $w_{1/} w_2 = 3/1$, $w_{1/} w_3 = 9/1$, $w_{1/} w_4 = 1/1$, $w_{1/} w_5 = 3/1$, $w_{1/} w_6 = 9/1$, $w_{1/} w_7 = 9/1$. With $w_1 = 1$, then $w_2 = 1/3$, $w_3 = 1/9$, $w_4 = 1$, $w_4 = 1$, $w_5 = 1/3$, $w_6 = 1/9$, and $w_7 = 1/9$. The corresponding matrix notation is given as:

$$\begin{vmatrix} 1/3 & -1 & 0 & 0 & 0 & 0 & 0 \\ 1/9 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 1/3 & 0 & 0 & 0 & -1 & 0 & 0 \\ 1/9 & 0 & 0 & 0 & 0 & -1 & 0 \\ 1/9 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{vmatrix} \times \begin{vmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \lambda_7 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{vmatrix}$$

Solving the system of equations provides the following values for the baseline set of coefficients:

$$\begin{aligned} \lambda_1 &= 0.3333 \\ \lambda_2 &= 0.1111 \\ \lambda_3 &= 0.0370 \\ \lambda_4 &= 0.3333 \\ \lambda_5 &= 0.1111 \\ \lambda_6 &= 0.0370 \\ \lambda_7 &= 0.0370 \end{aligned}$$

Table 0-12 provides an assessment of how well each initiative satisfies each criterion. These represent the criterion value scores, $v_k(a_i)$, assigned to each initiative-criteria combination.

Table 0-13 displays the baseline value scores, $V_0(a_i)$ for each initiative. These are calculated using the equation:

$$V_0(a_i) = 100 * \sum_{k=1}^{m} \lambda_k v_k(a_i) \text{ with } \sum_{k=1}^{m} \lambda_k = 1 \text{ and } 0 \le v_k(a_i) \le 1$$

for all k = 1,…,K; i= 1,…N

For example, the value score for a_1 is calculated as follows:

$V_0(a_i)$ =100*[(0.333)(0) +(0.111)(0.33) +

(0.037)(0)+(0.333)(0)+(0.111)(1)+(0.037)(0)+(0.037)(0)]= 14.8 ≈15.

The initiative a_4 has the highest score and thus is the ranked first priority.

Table 0-10: Strategic priorities time frame - description of energy investment initiatives that will be considered in prioritization.

Investment initiative	Description
a_1 No-action	Maintain the status quo grid supplied energy for power and cooling needs, and natural gas steam plant for heat.
a_2 Microturbine trigeneration (critical load)	Microturbines distributed generation of prime power including cogeneration of electricity and thermal energy for 5 buildings.
a_3 Microturbines trigeneration (base load)	Microturbines distributed generation of prime power including cogeneration of electricity and thermal energy for 46 buildings. This enables removal of an old steam boiler.
a_4 Microgrid of backup generators	Create a microgrid for using existing generators as backup power.
a_5 Photovoltaic Solar	Install solar PV on rooftops

Table 0-11: Strategic priorities time frame - criteria and criteria coefficients for energy security at the facility expressed as a percentage.

Criteria	Baseline coefficients expressed as a percentage
z_1 Quality prime power	33.3%
z_2 Reduced costs	11.1%
z_3 Increase renewable/alternative energy	3.7%
z_4 Provide proof-of principle/lessons learned	33.3%
z_5 Procure funding	11.1%
z_6 Reduce physical/non-physical vulnerability	3.7%
z_7 Reduce environmental impact	3.7%

Table 0-12 Strategic priorities time frame – Likert type assessment of initiatives across criteria, $v_k(a_i)$

	a_1 No action	a_2 Microturbine trigeneratoin (critical load)	a_3 Microturbines trigeneration (base load)	a_4 Microgrid of backup generators	a_5 Solar PV
z_1 Quality prime power	0	0.33	1	0.33	0
z_2 Reduced costs	0.33	0.66	1	0	0
z_3 Increase renewable/alternative energy	0	0	0	0	1
z_4 Provide proof-of principle/lessons learned	0	0.66	0.66	1	0.66
z_5 Procure funding	1	0.66	0.33	0.66	0.66
z_6 Reduce physical/non-physical vulnerability	0	0.66	0.66	1	0
z_7 Reduce environmental impact	0	0.66	1	0	0.33

Table 0-13: Strategic priorities time frame - the baseline value function scores for the five initiatives that are used to rank the initiatives.

	a_1 No action	a_2 Microturbine trigeneratoin (critical load)	a_3 Microturbines trigeneration (base load)	a_4 Microgrid of backup generators	a_5 Solar PV
Baseline value score	15	53	**77**	56	35
Baseline ranking	5th	3nd	**1st**	2rd	4th

4.4.3 Details of the Scenario-Based Preference Analysis

After reflection on the baseline rankings, a set of scenarios defined $S=\{s_1,\ldots,s_p\}$ was constructed and used to describe viewpoints of the multiple stakeholders serving as decision makers. These scenarios are different than those used in Karvetski and Lambert (2012). The previous analysis showed little change in the ranking of alternatives across scenarios. However, new scenarios were envisioned based on the relationship with an R&D problem frame (I^2) described in Hamilton et al. (2013a). Several of the scenarios were revised to be more distinguishable and to better align with distinct stakeholder priorities. The new set of five scenarios represented different stakeholders with distinct views or advocacy positions with regards to energy at military installations. Thus, a new set of five scenarios is described for this frame. Each scenario $s_k \in S_C$ can increase the preference levels of some criteria among the others while possibly decreasing preferences levels of other criteria. The baseline scenario, where there are no dominating emergent conditions, is indexed as s_0. The scenarios are indexed as follows:

- s_1 Islanding - Deterioration and vulnerability of commercial power grid infrastructure, increase in storm frequency and duration increase in brownouts and longer duration blackouts.
- s_2 Green Movement - Stricter federal energy efficiency, conservation, and renewable/alternative energy requirements.
- s_3 Cyber and Terrorism - Increase in cyber threats, increase in terrorism threats.

- s_4 Economic - Slow economic development, cutbacks in government spending
- s_5 Technology innovation - Lack of private investment in R&D, increased pressure for the government to provide proof-of-principle for emerging technology

These scenarios were used to reassess the baseline criteria preferences or weights under each scenario. These adjustments answer the following question: "Compared to a baseline scenario, which of the criteria becomes more important or less important under scenario s_k?" The answer to the question is categorized as a major decrease in importance, minor decrease in importance, minor increase in importance, or major increase in importance. For example, the first scenario s_1 describes that deterioration and vulnerability of the electric power grid to long term outages is becoming more of a concern, thus there is a minor increase in the importance of providing quality prime power and a minor decrease in the importance of reducing costs given the baseline criteria coefficients.

If λ_k increases under scenario s_j compared to the baseline scenario the coefficient of this criterion is adjusted through defining a constant $\alpha > 1$ and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k^{th} criterion is then

$$\lambda'_k = \alpha \times \lambda_k.$$

The set of constant multipliers are defined for this case study are {1/9, 1/3, 1, 3,9}, where a major decrease corresponds to a multiplier of 1/9, a minor decrease corresponds to a multiplier of 1/3, no change corresponds to a multiplier of 1, a minor increase corresponds to a multiplier of 3 and a major increase corresponds to a multiplier of 9. The new set of λ'_k are then normalized to sum to one. Table 0-14 displays how the baseline criteria coefficients are adjusted.

For example in the scenario s_1 Islanding. :

$$\lambda_{1,1}{}' = 0.3333 \times 3 = 0.0370$$
$$\lambda_{1,2}{}' = 0.1111 \times \frac{1}{3} = 1.0000$$
$$\lambda_{1,3}{}' = 0.0370 \times 1 = \ \ 0.0370$$
$$\lambda_{1,4}{}' = 0.3333 \times 1 = 0.3333$$
$$\lambda_{1,5}{}' = 0.1111 \times 1 = 0.1111$$
$$\lambda_{1,6}{}' = 0.0370 \times 1 = 0.0370$$
$$\lambda_{1,7}{}' = 0.0370 \times 1 = 0.0370$$

Normalization so that the criteria coefficients sum to one yields:

$$\lambda_{1,1} = 0.6279$$
$$\lambda_{1,2} = 0.0233$$
$$\lambda_{1,3} = 0.0233$$
$$\lambda_{1,4} = 0.2093$$
$$\lambda_{1,5} = 0.0698$$
$$\lambda_{1,6} = 0.0233$$
$$\lambda_{1,7} = 0.0233$$

Table 0-15 shows the above criteria coefficients for s_1 Islanding. The same process is applied for the other four scenarios. Table 0-15 displays the associated normalized adjustments in the criteria coefficients given the responses in Table 0-14. These criteria coefficients were then used with the value scores of Table 0-12 to produce a value score for each initiative under each scenario using the equation:

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

for all k = 1,…,K; i= 1,…N

Table 0-14: *Strategic priorities* time frame - elicitation of incremental adjustments importance of criteria across the five scenarios.

	s_1 Islanding	s_2 Green Movement	s_3 Cyber and Terrorism	s_4 Economic	s_5 Technology Innovation
z_1 Quality prime power	minor increase				
z_2 Reduced costs	minor decrease	minor decrease	minor decrease	MAJOR INCREASE	
z_3 Increase renewable/alternative energy		MAJOR INCREASE		MAJOR DECREASE	
z_4 Provide proof-of principle/lessons learned					minor increase
z_5 Procure funding				MAJOR INCREASE	
z_6 Reduce physical/non-physical vulnerability			MAJOR INCREASE		
z_7 Reduce environmental impact		MAJOR INCREASE		MAJOR DECREASE	

Table 0-15: *Strategic priorities* time frame - adjusted criteria coefficients expressed as a percentage for each criterion in each scenario

	s_1 Islanding	s_2 Green Movement	s_3 Cyber and Terrorism	s_4 Economic	s_5 Technology Innovation
z_1 Maximize quality, prime power	62.79%	21.95%	27.27%	12.29%	20.00%
z_2 Maximize financial benefit	2.33%	2.44%	3.03%	36.87%	6.67%
z_3 Maximize achievement of governmental goals	2.33%	21.95%	3.03%	0.15%	2.22%
z_4 Maximize technology innovation/spillover	20.93%	21.95%	27.27%	12.29%	60.00%
z_5 Procure funding	6.98%	7.32%	9.09%	36.87%	6.67%
z_6 Reduce physical/non-physical vulnerability	2.33%	2.44%	27.27%	1.37%	2.22%
z_7 Reduce environmental impact	2.33%	21.95%	3.03%	0.15%	2.22%

4.4.4 Sample of Output from *Strategic Priorities* Time Frame

Figure 0-1 describes output of the scenario-based preference analysis. Each energy security initiative is listed along the top axis and the priority score of the initiative is represented on the left axis (100 being the highest performing). The diamond represents the baseline scenario and the range bar represents the highest and lowest scores of each initiative across all considered scenarios. For example, the initiative a_4, microgrid of backup generators has a high value score under the baseline scenario; however, it is highly influenced by several of the scenarios, as shown by the large range above and below the baseline scenario diamond. On the other hand, initiatives a_3, microturbines with trigeneration for base load is relatively robust, i.e., has a high relative value score for all scenarios.

Table 0-16 shows the value scores and priority rankings, respectively, of the each initiative under each scenario. Notice that initiative, a_3, microturbines with trigeneration for base load, is the highest performing initiative under all scenarios and the value score dominates the others in several scenarios. However, the value score is very close to the value score for initiative a_4, microgrid of backup diesel generators in two scenarios (*economic* and *cyber and terrorism*). Under the *cyber and terrorism* perspective, the reliance on the natural gas utility and/or storage of large amounts of natural gas provides additional points of vulnerability compared to the microgrid of diesel generators.

As discussed in Chapter 3 there are several metrics for determining the robustness of initiatives.

Table 0-17 shows three metrics for measuring the robustness of initiatives. In all three metrics, the initiative a_3 *microturbines trigeneration (base load)* is considered the most robust. Table 0-18 shows two metrics for measuring the influence of scenarios. Notice that s_4 *economic* is the most influential scenario using the sum of squared ranking metric. The only scenario not to be considered influential in any of the metrics is s_3 *cyber and terrorism.* Table 0-19 summarizes the key results for this frame of priority setting for the case study. The results of this analysis can be used to creatively design new initiatives that would perform better across scenarios than the *a priori* initiatives considered. This is discussed in the next section on reframing.

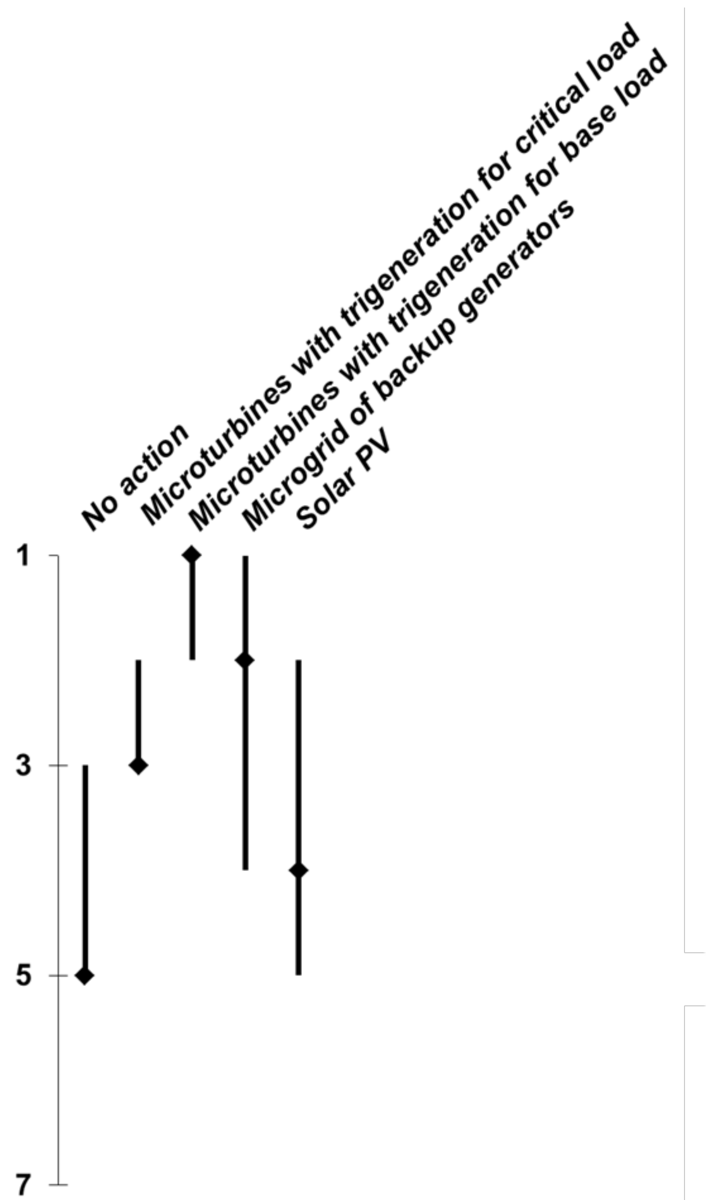

Figure 0-1: *Strategic priorities* time frame - sensitivity of ranking of initiatives across scenarios, $r_{i,j}$. The diamond represents the baseline ranking.

Table 0-16: *Strategic priorities* time frame - value scores, $V_j(a_i)$, of five initiatives and corresponding ranking, $r_{i,j}$ (in parentheses) across each scenarios (across each row).

	a_1 No action	a_2 Microturbine trigeneratoin (critical load)	a_3 Microturbines trigeneration (base load)	a_4 Microgrid of backup generators	a_5 Solar PV
Baseline	15 (5th)	53 (3nd)	**77 (1st)**	56 (2nd)	35 (4th)
s_1. Islanding	8 (5th)	44 (3rd)	**85 (1st)**	49 (2nd)	22 (4th)
s_2. Green Movement	8 (5th)	45 (3rd)	**65 (1st)**	37 (4th)	49 (2nd)
s_3. Cyber and Terrorism	10 (5th)	56 (3rd)	**73 (1st)**	70 (2nd)	28 (4th)
s_4.Economic	49 (3rd)	62 (2nd)	**71(1st)**	42 (4th)	33 (5th)
s_5. Technology Innovation	9 (5th)	59 (3rd)	73 (2nd)	**73 (1st)**	47 (4th)

Table 0-17: *Strategic priorities* time frame – three metrics for measuring the robustness of initiatives. The most robust initiative(s) for each metric are highlighted in bold.

Initiative	**Maximum ranking across scenarios (Robust initiatives min-max ranking)**	**Maximum regret (Robust initiatives minimize regret)**	**Number scenarios where initiative is in top three priority (Robust initiative is maximum)**
a_1 No-action	5	0.9	1
a_2 Microturbine trigeneration (critical load)	3	0.5	**6**
a_3 Microturbines trigeneration (base load)	**2**	**0**	**6**
a_4 Microgrid of backup generators	4	0.4	4
a_5 Photovoltaic Solar	4	0.7	1

Table 0-18: *Strategic priorities* time frame – two metrics to measure the influence of scenarios on energy security initiatives. The most influential scenario(s) for each metric are highlighted in bold.

Scenario	**Sum of square ranking changes relative to baseline**	**Percent change top three prioritized initiatives relative to baseline**
s_1 Islanding	0	0
s_2 Green Movement	0.2	**33%**
s_3 Cyber and Terrorism	0	0
s_4 Economic	**0.25**	**33%**
s_5 Technology Innovation	0.05	0

Table 0-19: *Strategic priorities* time frame - summary of key intermediate output of scenario-based preferences

Type of Result	Description
Robust initiative	The initiative ***a_3 microturbines with trigeneration (base load)*** is the most robust initiative. It is highly prioritized in the baseline scenario and remains the top ranked initiative for all scenarios but the scenario *s_5 technology innovation* where it drops to the second ranking. It has the largest $\max_{s_j \in S} r_{I,j}$ and the largest $rb(a_i)$.
Nearly robust initiatives	The initiative ***a_2 microturbines with trigeneration (critical load)*** is also robust scenario because it remains in the top three in all scenarios. The initiatives ***a_4 microgrid of backup generators*** is a nearly robust initiative. It is ranked second in the baseline scenario and in several other scenarios. There are two scenarios which drop the priority of this scenario to fourth. These include the *s_2 green movement* scenario and the *s_4 economic* scenario.
Influential scenarios	The ***s_4 economic*** scenario is the most influential followed by ***s_2 green movement*** and ***s_5 technology innovation*** scenarios. This is based on scores for each combination of conditions representing the sum of square ranking (SSRC) changes of the ranking values in comparison to the baseline ranking.
Scenarios that change the top priorities	The ***s_2 green movement*** and ***s_4 economic*** scenarios both change the top three ranked initiatives relative to the baseline.
Scenarios that decrease initiatives in priority relative to baseline	The ***s_s green movement and s_4 economic*** scenario decrease the priority of the initiatives a_2 *microturbines with trigeneration (critical load)* and *a_4 microgrid of backup generators*
Scenarios that increase initiatives in priority relative to baseline	The ***s_4 economic*** scenario increases the priority of a_1 no action. The ***s_s green movement*** scenario increase the priority of the initiatives a_5 *solar PV.*
Initiatives that fall in priority relative to baseline	The initiative ***a_3 microturbines with trigeneration (base load)*** is the first priority under the baseline scenario but falls to second priority under the *s_5 technology innovation*. The initiative ***a_4 microgrid of backup generators*** is second priority in the baseline scenario but decreases to fourth priority under two scenarios. These include the *s_2 green movement* scenario and the *s_4 economic* scenario. The initiative ***a_6 solar PV*** is ranked fourth in the baseline scenario but decreases in priority to fifth in the *s_4 economic* scenario**.**
Initiatives that rise in priority relative t baseline	The initiative ***a_5 microturbines with trigeneration (critical load)*** is ranked third in the baseline scenario but increases to second priority under the scenario *s_4 economic.* The initiative ***a_1 No action*** is ranked fifth in the baseline scenario but increases to third priority under the *s_4 economic.* The initiative ***a_4 microgrid of backup generators*** is second priority in the baseline scenario but increases to first priority under the scenario *s_4 technology innovation*.

4.4.5 Reframing for Subsequent Time Frames

This section discusses the intermediate results of the current problem frame and how these inform the inputs to the next problem frame.

The economic scenario provides the most reprioritization of the initiatives. The criterion that is heavily weighted in this scenario is reduced costs. In reality, the metric used to measure this criterion is not adequate to measure the objective of reducing costs for all economic scenarios. The next frame can focus on various uncertainties involved with the economic valuation of initiatives. The next frame will break this down into criteria that will influence the financial benefit of distributed generation.

The initiatives *and* a_4 *microgrid of backup generator* is a nearly robust initiative. It is less prioritized in the s_2 *green movement* scenario because it does not include any renewable energy and does not reduce environmental impact. Combining this initiative with either solar PV or microturbines trigeneration would improve the evaluation under this scenario. Also, the *islanding scenario provides* reduces the robustness of both the a_4 *microgrid of backup generator* and a_2 *microturbines with trigeneration (critical load)* because they are not able to provide long-term support to the critical load. If these two initiatives were combined it would increase the ability of the revised initiative to provide quality prime power. The initiative a_4 *microgrid of backup generator* is also less prioritized in the s_4 *economic* scenario because it does not provide as much as of an opportunity to reduce costs according to a traditional lifecycle cost analysis. A combination of backup generators and microturbines both on the same microgrid could be an improved initiative in this scenario.

The initiative a_5 *solar PV* is ranked fourth under the *green movement* scenario. However, it has a low ranking in the baseline scenario. The criterion driving the performance in the baseline scenario is *provide quality prime power*. Combining solar with battery or with backup generators or other backup generating sources will improve its intermittent nature and thus improve the evaluation in this criterion. This will be considered for the next frame.

The most robust initiatives are a_3 *microturbines for trigeneration (base load)*, a_2 *microturbines for trigeneration (base load)* and a_3 *microgrid of backup generators*. The next frame will focus on a more detailed analysis of these three initiatives. The criteria z_4 *provide proof-of-principle*, z_5 *procure funding* and z_6 *reduce physical/non-physical vulnerability* are no longer as relevant to distinguish between the detailed design. The criterion, z_2 *reduce costs* becomes more relevant for distinguishing between designs when considering various economic scenarios so this criterion will be broken into sub criteria in the next frame. A summary of the input, intermediate output, response to reframing questions, and reframing decisions is provided in Table 0-20.

Table 0-20: *Strategic priorities* time frame - reporting of criteria, initiatives, scenarios, intermediate results and reframing of scenario-based preferences

Input	Output	Reframing Questions	Reframing
Five initiatives *No action* *Bury lines* *Microturbine –trigen (critical load)* *Microturbine-trigen (base load)* *Microgrid of backup generators* *Solar PV*	**Three robust initiatives** *Microturbine –trigen (critical load)* *Microturbine-trigen (base load)* *Microgrid of backup generators*	Combining microgrids with various configurations of microturbines and solar PV are considered for the next frame.	**Five original initiatives eliminated** **Three new/combination initiatives** **One initiative maintained** *Microgrid backup generators*
Seven criteria *Quality, prime power for five buildings* *Reduced costs* *Increase renewable/alternative energy* *Provide proof-of-principle, lessons learned* *Procure funding* *Reduce physical/non-physical vulnerability* *Reduce environmental impact*		Several criteria were no longer as relevant for distinguishing the new set of initiatives. New sub-criteria were envisioned in order to better distinguish initiatives under the new set of economic inspired scenarios.	**Four criteria eliminated** *Reduce physical/non-physical vulnerability* *Procure funding* *Provide proof-of-principle,* **Three new sub-criteria** *Capital costs/installed capacity* *Peak shaving capability* *demand response capability* **Three criteria maintained** *Quality, prime power for five buildings* *Increase Renewable/alternative energy* *Reduce environmental impact*
Five scenarios *Islanding* *Green Movement* *Cyber and Terrorism* *Economic* *Technology Innovation*	**Three influential scenario** *Economic* *Renewable Movement* *Technology Innovation*	Four new scenarios envisioned further distinguishing the new and revised set of initiatives.	**Four new scenarios** *Service charge* *Time of day* *Demand response* *Renewable value streams*

4.5 Fourth Time Frame – Distributed Generation Design Priorities for an Installation

4.5.1 Overview

The fourth time frame (I^4) – distributed generation design priorities for an installation - is similar to I^1 and I^3 in that it is priority setting from the perspective of an individual installation. In this time frame, a microgrid with distributed generation has been selected for more detailed design. Several configurations of microgrids with distributed generation are selected to be prioritized. The fourth frame will use the results of previous frames of scenario-based preferences to inform the elements $\{A^4, Z^4, S^4\}$. The distributed generation design frame (I^4) will prioritize six initiatives using seven criteria under four scenarios of future emergent conditions. The frame will provide outputs that describe the robustness of each initiative and the influence or risk that each scenario provides. The frame will also discuss the relationship of the input to the output of previous frames as well as the relationship of the output to subsequent frames (I^5, I^6,…).

4.5.2 Baseline Analysis

The second frame will use the results of previous frames of scenario-based preferences to inform the elements $\{A^4, Z^4, S^4\}$ for frame I^4. The highly prioritized initiatives in the previous frame were various configurations of microturbines and the microgrids of backup generators. For this frame, a microgrid is included as an element of each initiative. This frame evaluated various combinations of microgrids and microturbines, solar PV, and backup generators. The Department of Defense defines a microgrid as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode" (DOE, 2011). There are many possible configurations of microgrids. Several configurations were selected based for prioritization. The initiatives are described in Table 0-21

The consideration of the *economic* scenario in the previous frame provided the most re-ranking of initiatives. The main criterion that was emphasized in this scenario is *reduced costs*. The metric used to measure achievement of this criterion is the twenty-year net present lifecycle value. One of the most influential factors that change the economics of distributed generation is the business model of electric utility providers. Thus several additional metrics were derived to measure the ability to reduce costs, the focus on which might shift in importance under various utility business models.

The seven criteria used in this frame are listed in Table 0-22. The baseline set of criteria coefficients were assessed using swing-weighting technique. The criterion, Z^1 was deemed the most important. The relative worth ratios were then assessed answering the question: Given the criterion Z^1 and $Z^{y,}$ what is the relative worth of exchanging z^{1o} for z^{1*} compared to exchanging z^{yo} for z^{y*}. The worth ratio for Z^1 is set so that $w_1 = 1$. The worth ratios were assess as follows: $w_{1/}w_2 = 9/1$, $w_{1/}w_3 = 9/1$, $w_{1/}w_4 = 9/1$, $w_{1/}w_5 = 3/1$, $w_{1/}w_6 = 3/1$, $w_{1/}w_7 = 1/1$. With $w_1 = 1$, then $w_2 = 1/3$, w_3

= 1/9, w_4 = 1, w_4 = 1, w_5= 1/3, w_6 = 1/9, and w_7 = 1/9. The corresponding matrix notation is given as:

$$\begin{vmatrix} 1/9 & -1 & 0 & 0 & 0 & 0 & 0 \\ 1/9 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1/9 & 0 & 0 & -1 & 0 & 0 & 0 \\ 1/3 & 0 & 0 & 0 & -1 & 0 & 0 \\ 1/3 & 0 & 0 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{vmatrix} \times \begin{vmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \lambda_7 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{vmatrix}$$

Solving the system of equations provides the following values for the baseline set of coefficients:

$$\begin{aligned} \lambda_1 &= 0.3333 \\ \lambda_2 &= 0.0370 \\ \lambda_3 &= 0.0370 \\ \lambda_4 &= 0.0370 \\ \lambda_5 &= 0.1111 \\ \lambda_6 &= 0.1111 \\ \lambda_7 &= 0.3333 \end{aligned}$$

Table 0-23 provides an assessment of how well each initiative satisfies each criterion. These represent the criterion value scores, $v_k(a_i)$, assigned to each initiative-criteria combination.

Table 0-24 displays the baseline value scores, $V_0(a_i)$ for each initiative. These are calculated using the equation:

$$V_0(a_i) = 100 * \sum_{k=1}^{m} \lambda_k v_k(a_i) \text{ with } \sum_{k=1}^{m} \lambda_k = 1 \text{ and } 0 \le v_k(a_i) \le 1$$

for all k = 1,…,K; i= 1,…N

For example, the value score for a_1 is calculated as follows:

$V_0(a_i)$ = (0.333)(0) +(0.037)(1) +

(0.037)(1)+(0.037)(0.33)+(0.111)(0)+(0.111)(0)+(0.333)(0.33) = 19.6 ≈20.

The initiative a_4 has the highest value score of 75 and thus is the ranked first priority.

Table 0-21: ***Distributed generation design*** **time frame - description of initiatives (microgrid configurations) that will be considered in prioritization.**

Microgrid Configurations	Description
a_1 Backup generators	This allows backup of critical load. Backup generators could be used to provide demand response and peak shaving capability.
a_2 Microturbines trigen (critical load)	Combined heat and power sized to the max critical electrical load. This would be intended to run continuously near capacity.
a_3 Microturbines trigen (critical load), thermal storage	Combined heat and power sized to the max critical electrical load. This would be intended to run continuously near capacity. Thermal storage allows microturbines to precool/heat buildings before peak demand hours.
a_4 Microturbines trigen (electrical base load)	Combined heat and power sized to the average base electrical load. This would be intended to run continuously near capacity. Additional low solar would help shave peak demands.
a_5 Microturbines trigen (thermal base load), backup generator, low solar	Combined heat and power sized to the average thermal load. This would be intended to run continuously near capacity. Backup generators and solar provide demand response and peak shaving capability.
a_6 High solar and high battery storage	This combination can provide demand response and peak shaving capability.

Table 0-22: *Distributed generation design* time frame - criteria and criteria coefficients (shown as a percentage) for energy security at the facility of the demonstration

Criteria	Baseline Coefficient
z_1 Maximize kwh onsite energy	33.33%
z_2 Decrease standby charges	3.70%
z_3 Increase demand response capability	3.70%
z_4 Increase peak shaving capability	3.70%
z_5 Reduce carbon emissions	11.11%
z_6 Increase renewable energy	11.11%
z_7 Decrease levelized cost of energy	33.33%

Table 0-23: *Distributed generation design* time frame – Likert type assessment of initiatives across criteria, $v_k(a_i)$,

	a_1 Microgrid backup generators	a_2 Microturbines trigen (critical load)	a_3 Microturbines trigen (critical load), thermal storage	a_4 Microturbines trigen (base load),	a_5 Microturbines trigen (thermal base load), backup gen, low solar	a_6 High solar and high battery storage
z_1 Maximize kwh onsite energy	0	0.333	0.333	1	0.67	0.67
z_2 Decrease standby charges	1	0.333	0.333	0.333	0.67	0
z_3 Increase demand response capability	1	0	0	0	0.333	1
z_4 Increase peak shaving capability	0.333	0	0.333	0	0.333	1
z_5 Reduce carbon emissions	0	0.333	0.333	0.67	1	0.67
z_6 Increase renewable energy	0	0	0	0	0.333	1
z_7 Decrease levelized cost of energy	0.33333 0.333	0.6666666 67	0.66666 6667	1	1	0

Table 0-24: *Distributed generation design* time frame - the baseline value function scores and associated rankings for the six initiatives.

	a_1 Microgrid backup generators	a_2 Microturbines trigen (critical load)	a_3 Microturbines trigen (critical load), thermal storage	a_4 Microturbines trigen (base load),	a_5 Microturbines trigen (thermal base load), backup gen, low solar	a_6 High solar and high battery storage
Baseline value score	20	38	40	**75**	75	48
Baseline ranking	6th	5th	4th	**1st**	1st	3rd

4.5.3 Details of the Scenario-Based Preference Analysis

After reflection on the baseline rankings, a set of scenarios defined $S=\{s_1,\ldots,s_p\}$ was constructed. These scenarios are derived from concerns over transitioning business models in the utility sector. Much of the U.S. electric power sector has changed little over the past 100 years. A recent report written by Peter Kind discusses recent technological and economic changes, or *disruptive challenges*, that are expected to transform the electric utility industry (Edison Electric Institute, 2013). According to the report, these challenges arise due to a convergence of factors, including: falling costs of distributed generation and other distributed energy resources (DER); development of new DER technologies; increasing customer, regulatory, and political interest in demand side management technologies (DSM); government programs to incentivize selected technologies; the declining price of natural gas; slowing economic growth trends; and rising electricity prices in certain areas of the country. Similarly, according to the report America's Power Plan (Harvey and Aggarwal, 2014) the "electricity system in America, and in many other nations, is in the early days of a radical makeover that will drastically reduce greenhouse gas emissions, increase system flexibility, incorporate new technologies, and shake existing utility business models." According to Peter Kind (2013), the financial risks created by disruptive challenges include declining utility revenues, increasing costs, and lower profitability potential, particularly over the long-term. As most utility business models are based on the quantity of energy sold, the increasing market penetration of DER and DSM programs will reduce utility revenues. Direct metering of DER, higher costs to integrate DER, and subsidies for DSM will result in the potential for a squeeze on profitability and, thus, credit metrics. Some utilities argue that existing rate recovery and incentive frameworks don't cover the cost of serving customers who install distributed generation systems (Burks et al. 2013). In the current business models, utilities are obligated to plan, build, and maintain the full system's power needs (including energy capacity costs, backup power generation, wires, people, fuel, and so forth), despite being largely cut out of that self-generating customer's revenue stream. The customers, who eventually bear this cost burden, in the form of higher rates, are generally those who cannot afford distributed generation in the first place. As DER penetration increases, so might political pressure to undo these cross subsidies

The top policy recommendations of America's Power Plan include: 1) moving away from rate-of-return regulation; use performance-based regulation that gives utilities the freedom to innovate or call on others for specific services; and separate the financial health of the utility from the volume of electricity it sells. 2) creating investor certainty and low-cost financing for renewable energy by steadily expanding Renewable Electricity Standards to provide a long-term market signal and 3) encouraging distributed generation by acknowledging customers' right to generate their own energy, by charging them a fair price for grid services, and by paying them a fair price for the grid benefits they create.

The scenarios developed for this time frame include several potential utility business models. Each scenario $s_k \in S_C$ can increase the preference levels of some criteria among the others while possibly decreasing preferences levels of other criteria. The baseline scenario, where there are no dominating emergent conditions, is indexed as s_0. The scenarios are indexed as follows:

- *s_1 Service charge* - This scenario presents the concern that there will be political pressure to change utility business model so that non-distributed energy resource (DER) customers are not subsidizing DER customers. In this scenario, a monthly service charge is the dominating part of the utility bill.
- *s_2 Time of day* – This scenario assumes that charges based on time of day drive utility business model.
- *s_3 Demand response* - This scenario assumes that a large portion of the utility bill is based on incentives to change demand. Demand response (also known as load response) is end-use customers reducing their use of electricity in response to power grid needs, economic signals from a competitive wholesale market or special retail rates.
- *s_4 Renewable value streams* – This scenario describes the economic value that could be derived in the renewable energy credit market.

These scenarios were used to reassess the baseline criteria preferences or under each scenario. Table 0-25 displays how the baseline criteria coefficients are adjusted. These adjustments answer the following question: “Compared to a baseline scenario, which of the criteria becomes more important or less important under scenario s_k?”

The answer to the question is categorized as a major decrease in importance, minor decrease in importance, minor increase in importance, or major increase in importance. For example, the scenario s_2 describes increasing peak shaving is becoming more of a concern, and levelized cost and standby charges are less of a priority given the baseline criteria coefficients.

If λ_k increases under scenario s_j compared to the baseline scenario the coefficient of this criterion is adjusted through defining a constant $\alpha > 1$ and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k^{th} criterion is then

$$\lambda'_k = \alpha \times \lambda_k.$$

The set of constant multipliers are defined for this case study are {1/9, 1/3, 1, 3,9}, where a major decrease corresponds to a multiplier of 1/9, a minor decrease corresponds to a multiplier of 1/3, no change corresponds to a multiplier of 1, a minor increase corresponds to a multiplier of 3 and a major increase corresponds to a multiplier of 9. The new set of λ'_k are then normalized to sum to one.

For example in the scenario s_1 Service charge:

$$\lambda_{1,1}{}' = 0.3333 \times 1/9 = 0.0370$$
$$\lambda_{1,2}{}' = 0.0370 \times 9 = 0.3333$$
$$\lambda_{1,3}{}' = 0.0370 \times 1 = 0.0370$$
$$\lambda_{1,4}{}' = 0.0370 \times 1 = 0.0370$$
$$\lambda_{1,5}{}' = 0.1111 \times 1 = 0.1111$$
$$\lambda_{1,6}{}' = 0.1111 \times 1 = 0.1111$$
$$\lambda_{1,7}{}' = 0.3333 \times 1 = 0.3333$$

Normalization so that the criteria coefficients sum to one yields:

$$\lambda_{1,1} = 0.0370$$
$$\lambda_{1,2} = 0.3333$$
$$\lambda_{1,3} = 0.0370$$
$$\lambda_{1,4} = 0.0370$$
$$\lambda_{1,5} = 0.1111$$
$$\lambda_{1,6} = 0.1111$$
$$\lambda_{1,7} = 0.3333$$

The same process is applied for the other three scenarios. Table 0-26 displays the associated normalized adjustments in the weight of each criterion given the responses in Table 0-25. These coefficients were then used with the value scores of Table 0-23 to produce a value score for each initiative under each scenario using the equation:

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{ with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

for all k = 1,…,K; i= 1,…N

Table 0-25: *Distributed generation design* time frame - elicitation of adjustments to the importance of criteria across the four scenarios.

	s_1. Service charge	s_2. Time of day	s_3.Demand response	s_4. Renewable value streams
z_1 Maximize kwh onsite energy	MAJOR DECREASE			
z_2 Decrease standby charges	MAJOR INCREASE	MAJOR DECREASE	MAJOR DECREASE	MAJOR DECREASE
z_3 Increase demand response capability			MAJOR INCREASE	
z_4 Increase peak shaving capability		MAJOR INCREASE		
z_5 Reduce carbon emissions				
z_6 Increase renewable energy				MAJOR INCREASE
z_7 Decrease levelized cost of energy		MAJOR DECREASE	MAJOR DECREASE	MAJOR DECREASE

Table 0-26: *Distributed generation design* time frame - adjusted criteria coefficients expressed as a percentage for each criterion in each scenario

	s_1. Service charge	s_2. Time of day	s_3.Demand response	s_4. Renewable value streams
z_1 Maximize kwh onsite energy	3.70%	34.47%	34.47%	21.37%
z_2 Decrease standby charges	33.33%	0.43%	0.43%	0.26%
z_3 Increase demand response capability	3.70%	3.83%	34.47%	2.37%
z_4 Increase peak shaving capability	3.70%	34.47%	3.83%	2.37%
z_5 Reduce carbon emissions	11.11%	11.49%	11.49%	7.12%
z_6 Increase renewable energy	11.11%	11.49%	11.49%	64.12%
z_7 Decrease levelized cost of energy	33.33%	3.83%	3.83%	2.37%

4.5.4 Sample output from Distributed Generation Design time frame

Figure 0-2 describes results of the scenario-based preference analysis. Each energy security initiative is listed along the top axis and the ranking score of the initiative is represented on the left axis. The diamond represents some baseline scenario and the range bar represents the highest and lowest ranking of each initiative across all considered scenarios. For example, the initiative a_6 *high solar and high battery* is ranked third in the baseline scenario; however, it is highly influenced by one or more of the scenarios, as shown by the large range above and below the baseline scenario diamond. On the other hand, initiative a_5, remains in the top two priority in all scenarios considered in this frame.

Table 0-27 shows the value scores and priority rankings, respectively, of the each initiative under each scenario. The initiatives, a_5 *Microturbines trigen (thermal base load), backup gen, low solar and* a_4 *Microturbines trigen (base load)* are the highest priority initiative in the baseline scenario and remain in the top three priority under all scenarios. However, their value scores are much lower compared to the top ranked initiative (*high solar and high battery*) in three of the scenarios.

As discussed in Chapter 3 there are several metrics for determining the robustness of initiatives. Table 0-28 shows four metrics for measuring the robustness of initiatives. The initiative a_5 *microturbines trigen (thermal base load), backup generator, low solar)* is considered the most robust is all three metrics.

Table 0-29 shows two metrics for measuring the influence of scenarios. Notice that s_1 *service charge* is the most influential scenario for both metrics.

Table 0-30 summarizes the key results for this frame of priority setting for the case study. The results of this analysis can be used to creatively design new initiatives that would perform better across scenarios than the *a priori* initiatives considered.

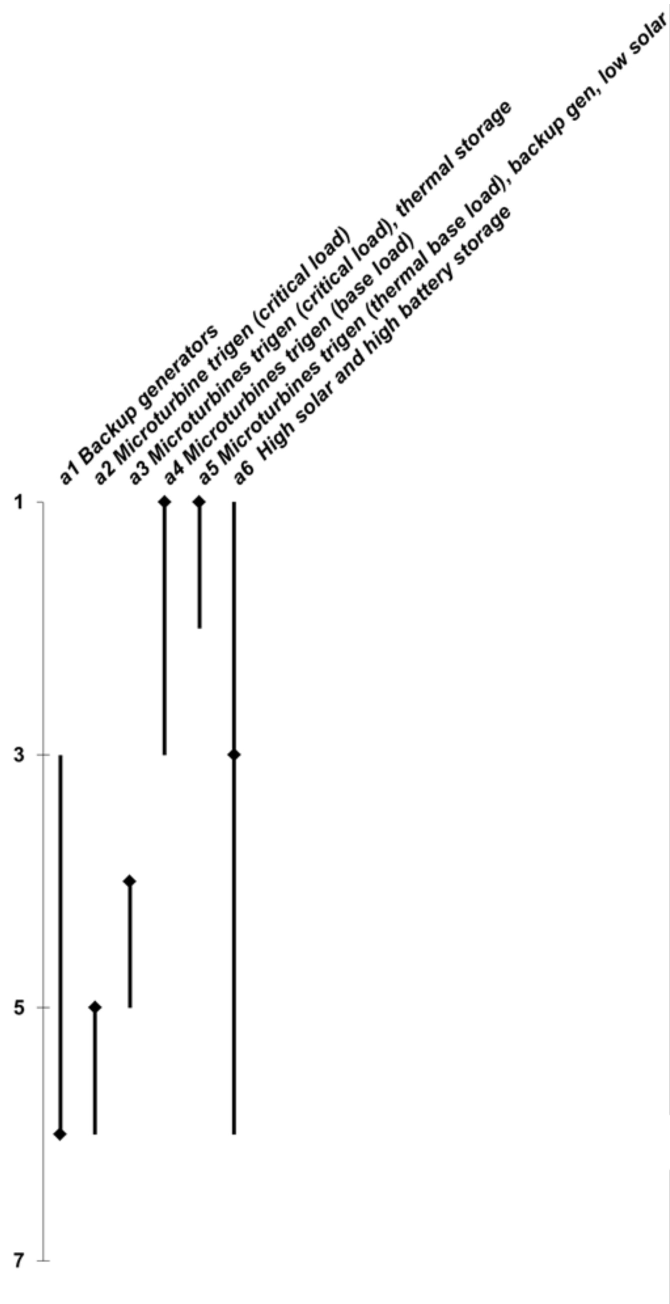

Figure 0-2: ***Distributed generation design*** **time frame - Sensitivity of priority scores for several microgrid initiatives under scenarios of deep uncertainty. The diamond represents the baseline ranking**

Table 0-27: *Distributed generation design* time frame - the value score of six initiatives and corresponding ranking (in parentheses) across each scenarios (across each row).

	a_1 Microgrid backup generators	a_2 Microturbines trigen (critical load)	a_3 Microturbines trigen (critical load), thermal storage	a_4 Microturbines trigen (base load)	a_5 Microturbines trigen (thermal base load), backup gen, low solar	a_6 High solar and high battery storage
Baseline	20 (6th)	38 (5th)	40 (4th)	**75 (1st)**	**75 (1st)**	48 (3rd)
S1. Service charge	49 (3rd)	38 (5th)	40 (4th)	56 (2nd)	**75 (1st)**	28 (6th)
S2. Time of day	17 (6th)	18 (5th)	30 (4th)	46 (3rd)	55 (2nd)	**80 (1st)**
S3. Demand response	37 (4th)	18 (6th)	19 (5th)	46 (3rd)	55 (2nd)	**80 (1st)**
S4. Renewable value streams	4 (6th)	11 (5th)	12 (4th)	29 (3rd)	47 (2nd)	**88 (1st)**

Table 0-28: *Distributed generation design* time frame – two metrics for measuring the robustness of initiatives.

Initiative	Maximum ranking across scenarios (Robust initiatives min-max ranking)	Maximum regret (Robust initiatives minimize regret)	Number scenarios where initiative is in top three priority (Robust initiative is maximum)
a_1 Backup generators	6	0.96	1
a_2 Microturbines trigen (critical load)	6	0.88	0
a_3 Microturbines trigen (critical load) thermal storage	4	0.86	0
a_4 Microturbines trigen (electrical base load)	3	0.67	**5**
a_5 Microturbines trigen (thermal base load), backup generator, low solar	**2**	**0.47**	**5**
a_6 High solar and high battery storage	6	0.63	**4**

Table 0-29: *Distributed generation design* time frame –two metrics to measure the influence of scenarios on energy security initiatives.

Scenario	Sum of square ranking changes relative to baseline	Percent change to top three prioritized initiatives relative to baseline
s_1 Service charge	**0.27**	**33%**
s_2 Time of Day	0.13	0
s_3 Demand response	0.216	0
s_4 Renewable value streams	0.13	0

Table 0-30: *Distributed generation design* time frame - summary of key intermediate results of the scenario analysis

Type of Result	Description
Robust initiative	The initiative ***a_5 microturbines trigen (thermal base load), backup generator, low solar*** is a robust initiative. It is highly prioritized in the baseline scenario and remains the in the top two priority for all scenarios. The initiative ***a_4 Microturbines trigen (electrical base load)*** is also a highly robust initiative as it remains in the top three priority in all scenarios.
Nearly robust initiatives	The initiatives ***a_6 High solar and high battery storage*** is a nearly robust initiative. It is highly prioritized in the baseline scenario and remains highly prioritized in all but one scenario.
Influential scenarios	The ***s_1 service charge*** scenario provides the most changes to prioritization of initiatives based on the sum of square ranking (SSRC) changes of the ranking values in comparison to the baseline ranking. The ***s_3 Demand response*** provides the second most changes to prioritization of initiatives.
Scenarios that change the top priorities relative to baseline	The ***s_1 service charge*** scenario provides change the top three ranked initiatives relative to the baseline.
Scenarios that decrease initiatives in priority relative to baseline	The ***s_2 renewables value stream*** scenario decreases the priority of the initiatives *a_3 microturbines trigen (critical load), thermal storage* and *a_4 microturbines trigen (electrical base load)*. The scenario ***s_1 service charge*** decreases the priority *a_6 High solar and high battery storage*
Scenarios that increase initiatives in priority relative to baseline	The ***s_1 service charge*** scenario increases the priority of the initiative *a_1 microgrid of backup generator*
Initiatives that fall in priority relative to the baseline scenario	The ***a_6 High solar and high battery storage*** initiative drops in priority from the third priority to the bottom ranked initiative under the service charge scenario.
Initiatives that rise in priority relative to the baseline scenario	The initiative ***a_1 Microgrid of backup generator*** rises in priority from the bottom initiative to the third priority initiative under the service charge scenario. Initiative ***a_6 high solar and high battery*** is third priority in the baseline scenario but increases to first priority under three of the five scenarios.

4.5.5 Reframing for Subsequent Time Frames

The results of the previous frame can be used to revise the input into the next frames. A very robust initiative in the fourth frame is a_5 *microturbines CHP base load, backup gen, low solar,* however it does not perform as well as a_6 *high solar and high* battery in three of the scenarios. This is because it is not able to respond to demand quite as well, nor reduce peak daytime demands, especially in the summer months. If the initiative a_5 *microturbines CHP base load, backup gen, low solar* included batteries as part of the system this may increase its ability to reduce peak demand and/or respond to request from the utility grid to reduce demand at a short notice. Other improvements in initiatives, criteria, and scenarios are to be determined for a future frame (Table 0-31).

The iterative reframing process can continue until it meets the conditions of for justifying terminating or pausing the analysis described in Chapter 3. Namely, that no new or revised initiatives, criteria, or scenarios are identified.

Table 0-31: *Distributed generation design* time frame - reporting of criteria, initiatives, scenarios, intermediate output and reframing of scenario-based preference model

Input	Output	Reframing Questions	Reframing
Six initiatives *Backup generators* *Microturbines trigen (critical load)* *Microturbines trigen (critical load) thermal storage* *Microturbines trigen (electrical base load)* *Microturbines trigen (thermal base load), backup generator, low solar* *High solar and high battery storage*	**Three robust initiatives** *Microturbines CHP base load, backup gen, low solar* *High solar and high battery*	The next frame could consider combining battery backup with the initiative a_5 Microturbines CHP base load, backup gen, low solar to improve the performance in the time of day and demand response scenarios	Recommended for a future frame
Six criteria *Maximize kwh onsite energy* *Decrease standby charges* *Increase response capability* *Increase peak shaving capability* *Reduce carbon emissions* *Increase renewable energy* *Minimize levelized cost of energy*		Recommended for a future frame	Recommended for a future frame
Four scenarios *Service charge* *Time of day* *Demand charge* *Renewable value streams*	**Four influential scenarios** (*Service charge* most influential)	Recommended for a future frame	Recommended for a future frame

4.6 Discussion of Evolution across Time Frames

This section describes several overall results of the application of scenario-based preferences across time frames. In the first frame, the highest priority initiative was microturbines sized to support electricity and thermal needs for the entire forty-six buildings in the complex. The initiative that was the highest priority in the last frame was not included in the first frame. This initiative involves installing enough microturbines to support the thermal demands, which would also meet a majority of the electrical demands. The rest of the electrical demand could be met through both grid-supplied electricity and solar energy. Integrating backup generators (and possibly batteries) would improve the reliability and, thus, reduce any service charge potentials, allowing the facility to take advantage of changes in utility models such as time of day pricing and demand management incentives. Also, if the size of the trigeneration microturbines are more closely matched with the thermal load, the carbon dioxide emissions reduction would be the greatest. If the process had terminated after the first frame, the choice to install a large amount of microturbines may have been pursued as the highest priority. Also, the scenarios of the changing business models may not have been discussed. These changing business models impact the choice of distributed generation size, type and operation.

4.7 Chapter Summary

This case study extended the previous efforts of scenario-based preference modeling of Karvetski and Lambert (2012) and Hamilton et al. (2013a) to illustrate the process of iterating across multiple time frames. Section 4.3 discussed the output of the previous time frames how the initiatives, criteria, and scenarios could be evolved in subsequent time frames. Section 4.4 and 4.5 described in detail in two additional frames and suggested input to future frames. Repeating the process in multiple time frames was successful in that

- Three initiatives were eliminated,
- Five new/modified initiatives were identified,
- Five new criteria were identified, and
- Eight new risk scenarios were identified.

The initial scenario-based preference analysis described in Karvetski et al. suggested that the most robust initiative was to install natural gas microturbines to support the electricity and thermal demand for all forty-six building in the area 300 of Fort Belvoir. Through iterative consideration of scenarios, a more adaptive approach is suggested that includes a smaller generating capacity of natural gas microturbines as part of a microgrid that leaves opportunity to add in renewables, energy storage, and other emergent technologies.

Case Study – Climate-Change and Coastal Infrastructure

5.1 Chapter Overview

Sources of risk and uncertainty are key drivers for natural resource and infrastructure priorities in coastal regions. This case study describes quantification of how scenarios of climate and other factors influence the priorities of coastal risk reduction and resilience initiatives through the use of scenario-based multicriteria analysis in multiple time frames. The uncertainties addressed herein include temperature, storm intensity and frequencies, precipitation, coastal populations, sea-level rise, other environmental stressors, economic activity and factors deemed relevant by agency stakeholders.

5.2 Background

This case study will address climate change planning for coastal regions. The effects and impacts of climate change are an important consideration for coastal infrastructure and ecological systems. Climate change may include changes in sea levels, alterations in the frequencies of extreme storms and droughts, direct effects of temperature change on atmospheric and hydrological processes, changes in wildfire activity, alterations of animal and plant ecology, and other phenomena of importance to natural resource and infrastructure systems (Karvetski et al, 2011b; Karvetski et al, 2011c). The tremendous range of projections as to the specific climate change impacts, their magnitude, timing, and geographic extent are a source of great uncertainty (Irias et al. 2011; Ayyub, 2012; Boon et al. 2012). These climate stressors may be in combination with changes in other driving forces such as population growth, demographic change including migration from rural to urban areas, increase in standard of living, competition between users, land-use change, and pollution of water resources (Jenicek, et al., 2011). The myriad combinations of uncertain factors pose a challenge to agencies who seek to prioritize portfolios of natural resource and infrastructure assets, projects, and policies to achieve multiple, sometimes competing mission objectives. This drives a need to prioritize initiatives that support the resiliency of infrastructure system within a decision-making framework (Ayyub, 2013).

The Executive Order "Preparing the United States for the Impacts of Climate Change" released in November 2013, requires that federal agencies that manage lands and waters complete an inventory and assessment of proposed and completed changes to their land and water related policies, programs, and regulations necessary to make the Nation's watersheds, natural resources, and ecosystems, and the communities and economies that depend on them, more resilient in the face of a changing climate. Executive Order 13514 required Federal agencies to develop Agency Adaptation Plans that evaluate the most significant climate change related risks to, and vulnerabilities in, agency operations and missions in both the short and long term, and outline actions that agencies will take to manage these risks and vulnerabilities. Each agency is required to develop, implement, and update comprehensive plans that integrate consideration of climate change into agency operations and overall mission objectives.

Among other agencies, the US Army Corps of Engineers (USACE) is charged with missions to provide engineering services to protect more than 12 million acres of public lands, more than 900 ports and harbors, nearly 14,000 miles of levees and 12,000 miles of commercial inland waterways, and 400 miles of coastal shoreline (Dalton et al. 2012). Nearly all of these missions are at some risk from potential effects of future climate and other global changes. USACE coordinates with other Federal agencies, both directly and through the multi-agency adaptation efforts coordinated by two US White House offices, the Council on Environmental Quality (CEQ) and the Office of Science and Technology Policy (OSTP) to address the effects of climate change to infrastructure systems (Dalton et al. 2012). The USACE and other government agencies must review and prioritize land and water related policies, programs, and regulations, to increase the resilience and decrease the vulnerability to the uncertain impacts of climate change.

USACE works with agencies to produce guidance for addressing climate change and sea level rise. This includes the development of Engineering Circular 1165-2-211 (2009) on sea-level change, and the current development of a new Civil Works Technical Letter based on that Circular for guidance to USACE operations on how to plan and respond to sea-level change at vulnerable projects. Other important reports include "Climate Change and Water Resources Management: A Federal Perspective" (USGS Circular 1331 2009), "Addressing Climate Change in Long-term Water Resources (USACE CWTS-10-02 2011)", "2012 Climate Change Adaption Plan and Report", and "Coastal Risk Reduction and Resilience" (USACE CWTS 2013-3).

The Civil Works Technical Letter provides guidance for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects. The technical guidance uses recent climate research by the Intergovernmental Panel on Climate Change (IPCC) for predictions of global mean sea-level. The technical guidance recommends that planning studies and engineering designs over the project life cycle, for both existing and proposed projects consider alternatives (both structural and nonstructural) that are formulated and evaluated for the entire range of possible future rates of sea-level change (SLC), represented by three scenarios of "low," "intermediate," and "high" sea-level change both "with" and "without" project conditions.

This case study will present two time frame of scenario-based preference analysis to identify and prioritize key uncertainties. The case thus describes a method for highlighting the emergent and future stressors that most matter to adaptive management of coastal infrastructure.

5.3 First Time Frame – Individual Measure Priorities for Coastal Risk Reduction and Resilience

5.3.1 Overview

The first time frame (I^1) prioritizes individual coastal risk reduction and resilience measures. The USACE recently published the paper "Coastal Risk Reduction and Resilience: Using the Full Array of Measures" which discusses USACE guidance on how to help reduce risks to coastal areas and improve resilience to coastal hazards through an integrated planning approach (US Army Corps of Engineers 2013). Coastal risk reduction and human and ecosystems resilience can be achieved through a variety of approaches including natural or nature-based features such as wetlands and dunes, nonstructural interventions such as building codes and emergency response and structural interventions such as seawalls and breakwaters. Each measure provides varying degrees of environmental and social benefits. These include benefits related to commercial and recreational fisheries, tourism, water supply, habitat for threatened and endangered species, and support for cultural practices. For example, breakwaters offer shoreline erosion protection by attenuating wave energy, but they can also provide recreational opportunities, and valuable aquatic habitat (US Army Corps of Engineers 2013).

5.3.2 Baseline Analysis

The initiatives to be prioritized are the nature, nature-based, nonstructural, and structural measures identified and described in the "Coastal Risk Reduction and Resilience: Using the Full Array of Measures" (US Army Corps of Engineers 2013). Table 0-1 provides the set A={a_1,...,a_N} of N measures used in this demonstration. The criteria used to evaluate the measures are based on the attributes for each measure that provide risk reduction and resilience. They include attributes such as reduced salinity intrusion, reduced wave overtopping, reduced erosion, etc. The left-hand column of Table 0-2 provides the set Z={Z^1,...,Z^k} of k criteria used in to evaluate the measures in this demonstration. Table 0-2 provides the value score $v_k(a_i) = v_k(z_i^k)$ for each initiative evaluated on each criterion. The baseline assessment assumes equal weights for each criterion (each $\lambda_k = 0.0588$).

Table 0-3 displays the baseline value scores, $V_0(a_i)$ for each initiative. These are calculated using the equation:

$$V_0(a_i) = 100 * \sum_{k=1}^{m} \lambda_k \, v_k(a_i) \text{ with } \sum_{k=1}^{m} \lambda_k = 1 \text{ and } 0 \le v_k(a_i) \le 1$$

for all k = 1,...,K; i= 1,...N

For example, the value score for a_1 is calculated as follows:

$V_0(a_i)$ = (0.0588)(1) + (0.0588)(0.667)+(0.0588)(1) + (0.0588)(0) + (0.0588)(0) (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) + (0.0588)(0) = 15.6 ≈16.

The initiatives a_2 and a_{10} have the highest value score of 22 and thus is the ranked first priority.

Table 0-1: Individual measures frame – set A={a_1,…,a_N} of initiatives (risk and resilience measures) to be prioritized

Natural and nature based	a_1. Dunes and beaches a_2. Vegetated features a_3. Oyster and coral reefs a_4. Barrier islands a_5. Maritime forest/shrub communities
Non-structural	a_6.Floodplain policy and management a_7. Floodproofing and impact reduction a_8. Flood warning and preparedness a_9. Relocation
Structural	a_{10}. Levees a_{11}. Storm surge barriers a_{12}. Seawalls and revetments a_{13}. Groins a_{14}. Detached breakwaters

Table 0-2: *Individual measures* time frame –Likert type assessment of initiatives across criteria, $v_k(a_i)$

Criteria	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
z_1.Breaking of offshore waves	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
z_2.Wave attenuation	0.66	0.66	0.66	1	1	0	0	0	0	1	1	0	0	0.66	0
z_3. Slow inland water transfer	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
z_4. Increased infiltration	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
z_5. Reduce erosion	0	0	0	0.66	1	0	0	0	0	0	0	0	0	0	0
z_6. Improve/control floodplain development	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
z_7. Reduce opportunity for damages	0	0	0	0	0	1	0.66	0.33	1	0	0	0	0	0	0
z_8. Improve natural coast environment	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
z_9. Increase community resilience	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
z_{10}. Do not increase flood potential elsewhere	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
z_{11}. Improve public awareness/responsibility	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
z_{12}. Surge attenuation	0	0	0	0	0	0	0	0	0	0.66	1	0	0	0	0
z_{13}. Reduce flooding	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
z_{14}.Risk reduction for vulnerable areas	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
z_{15}. Reduce wave overtopping	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
z_{16}. Shoreline stabilization behind structure	0	0	0	0	0	0	0	0	0	0	0	1	0.66	0.66	0
z_{17}. Reduce salinity intrusion	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 0-3: *Individual measures* time frame - the baseline value function scores and associated rankings for the fourteen initiatives.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
Baseline value score	16	**22**	16	10	12	18	16	14	18	**22**	18	18	4	8
Baseline ranking	7th	**1st**	7th	12th	11th	3rd	7th	10th	3rd	**1st**	3rd	3rd	14th	13th

5.3.3 Details of Scenario-Based Preference Analysis

Next, a set of scenarios $S=\{s_0, s_1,\ldots,s_5\}$ that are combinations of emergent/future conditions are identified are described below. For the purpose of this case study, five scenarios were assembled from frequently mentioned conditions in the Civil Works Technical Letter and other USACE documents.

s_1. *High LRSL* – Large increase in local relative sea level (LRSL)

s_2. *Coastal migration:* Increase in residential and commercial development and decrease in natural land cover, in combination with medium LRSL

s_3. *Temperature rise* Increase in both air and water temperatures in combination with decrease in maritime wildlife habitat and medium sea LRSL

s_4. *Precipitation increase*- Increase in precipitation increases runoff in combination with medium LRSL

s_5. *Severe storms* – Increase in frequency and severity of storms with strong winds and surge in combination with medium LRSL

The criteria are reevaluated for each of the scenarios as described in Chapter 3. These adjustments answer the following question: "Compared to a baseline scenario, which of the criteria becomes more important or less important under scenario s_k?" The answer to the question is categorized as a major decrease in importance, minor decrease in importance, minor increase in importance, or major increase in importance. Table 0-4 shows the adjusted priority of the criteria under considered stakeholder scenarios. For example, under the stakeholder scenario, s_4, *Precipitation* *increase*, there is a major increase the criteria *increased infiltration, reduce erosion and reduce flooding.* If λ_k increases under scenario s_j compared to the baseline scenario the coefficient of this criterion is adjusted through defining a constant $\alpha > 1$ and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k[th] criterion is then

$$\lambda_k' = \alpha \times \lambda_k.$$

The set of constant multipliers are defined for this case study are {1/9, 1/3, 1, 3,9}, where a major decrease corresponds to a multiplier of 1/9, a minor decrease corresponds to a multiplier of 1/3, no change corresponds to a multiplier of 1, a minor increase corresponds to a multiplier of 3 and a major increase corresponds to a multiplier of 9. The new set of λ_k' are then normalized to sum to one.

For example in the scenario s_1 High LSRL:

$$\lambda_{1,1}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,2}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,3}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,4}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,5}' = 0.0588 \times 3 = 0.1764$$
$$\lambda_{1,6}' = 0.0588 \times 9 = 0.5292$$
$$\lambda_{1,7}' = 0.0588 \times 9 = 0.5292$$
$$\lambda_{1,8}' = 0.0588 \times 9 = 0.5292$$
$$\lambda_{1,9}' = 0.0588 \times 9 = 0.5292$$
$$\lambda_{1,10}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,11}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,12}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,13}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,14}' = 0.0588 \times 9 = 0.5292$$
$$\lambda_{1,15}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,16}' = 0.0588 \times 1 = 0.0588$$
$$\lambda_{1,17}' = 0.0588 \times 3 = 0.1764$$

Normalization so that the criteria coefficients sum to one yields:

$$\lambda_{1,1} = 0.0164$$
$$\lambda_{1,2} = 0.0164$$
$$\lambda_{1,3} = 0.0164$$
$$\lambda_{1,4} = 0.0164$$
$$\lambda_{1,5} = 0.0492$$
$$\lambda_{1,6} = 0.1475$$
$$\lambda_{1,7} = 0.1475$$
$$\lambda_{1,8} = 0.1475$$
$$\lambda_{1,9} = 0.1475$$
$$\lambda_{1,10} = 0.0164$$
$$\lambda_{1,11} = 0.0164$$
$$\lambda_{1,12} = 0.0164$$
$$\lambda_{1,13} = 0.0164$$
$$\lambda_{1,14} = 0.1475$$
$$\lambda_{1,15} = 0.0164$$
$$\lambda_{1,16} = 0.0164$$
$$\lambda_{1,17} = 0.0492$$

The same process is applied for the other four scenarios. **Table 0-5** describes the normalized adjusted weight for each criterion in each scenario. These coefficients were then used with the value scores of **Table 0-2** to produce a value score for each initiative under each scenario using the equation:

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{ with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

for all k = 1,…,K; i= 1,…N

Table 0-4: *Individual measures* time frame - elicitation of incremental adjustments importance of criteria across the five scenarios.

Criteria	Scenarios				
	s_1 High LRSL	s_2 Coastal migration	s_3 Temperature rise	s_4 Precipitation increase	s_5 Severe storms
z_1.Breaking of offshore waves					MAJOR INCREASE
z_2.Wave attenuation					MAJOR INCREASE
z_3. Slow inland water transfer					
z_4. Increased infiltration				MAJOR INCREASE	
z_5. Reduce erosion	minor increase			MAJOR INCREASE	
z_6. Improve/control floodplain development	MAJOR INCREASE	MAJOR INCREASE			
z_7. Reduce opportunity for damages	MAJOR INCREASE				
z_8. Improve natural coast environment	MAJOR INCREASE	MAJOR INCREASE	MAJOR INCREASE		
z_9. Increase community resilience	MAJOR INCREASE	MAJOR INCREASE			MAJOR INCREASE
z_{10}. Do not increase flood potential elsewhere					
z_{11}. Improve public awareness/responsibility					MAJOR INCREASE
z_{12}. Surge attenuation					MAJOR INCREASE
z_{13}. Reduce flooding				MAJOR INCREASE	
z_{14}.Risk reduction for vulnerable areas	MAJOR INCREASE				MAJOR INCREASE
z_{15}. Reduce wave overtopping					MAJOR INCREASE
z_{16}. Shoreline stabilization behind structure		minor increase			
z_{17}. Reduce salinity intrusion	minor increase		MAJOR INCREASE		

Table 0-5: *Individual measures* time frame - corresponding normalized adjusted criteria coefficient expressed as a percentage for each criterion in each scenario (including baseline)

Criteria	Scenarios					
	Baseline	s_1 High LRSL	s_2 Coastal migration	s_3 Temperature rise	s_4 Precipitation Increase	s_5 Severe storms
z_1.Breaking of offshore waves	5.88%	1.64%	2.33%	3.03%	2.44%	12.33%
z_2.Wave attenuation	5.88%	1.64%	2.33%	3.03%	2.44%	12.33%
z_3. Slow inland water transfer	5.88%	1.64%	2.33%	3.03%	2.44%	1.37%
z_4. Increased infiltration	5.88%	1.64%	2.33%	3.03%	21.95%	1.37%
z_5. Reduce erosion	5.88%	4.92%	2.33%	3.03%	21.95%	1.37%
z_6. Improve/control floodplain development	5.88%	14.75%	20.93%	3.03%	2.44%	1.37%
z_7. Reduce opportunity for damages	5.88%	14.75%	2.33%	3.03%	2.44%	1.37%
z_8. Improve natural coast environment	5.88%	14.75%	20.93%	27.27%	2.44%	1.37%
z_9. Increase community resilience	5.88%	14.75%	20.93%	3.03%	2.44%	12.33%
z_{10}. Do not increase flood potential elsewhere	5.88%	1.64%	2.33%	3.03%	2.44%	1.37%
z_{11}. Improve public awareness/responsibility	5.88%	1.64%	2.33%	3.03%	2.44%	12.33%
z_{12}. Surge attenuation	5.88%	1.64%	2.33%	3.03%	2.44%	12.33%
z_{13}. Reduce flooding	5.88%	1.64%	2.33%	3.03%	21.95%	1.37%
z_{14}. Risk reduction for vulnerable areas	5.88%	14.75%	2.33%	3.03%	2.44%	12.33%
z_{15}. Reduce wave overtopping	5.88%	1.64%	2.33%	3.03%	2.44%	12.33%
z_{16}. Shoreline stabilization behind structure	5.88%	1.64%	6.98%	3.03%	2.44%	1.37%
z_{17}. Reduce salinity intrusion	5.88%	4.92%	2.33%	27.27%	2.44%	1.37%

5.3.4 Output from *Individual Measures* Time Frame

Table 0-6 describes the results of applying the scenario-based preference analysis. The table describes the measures ranked across the baseline and five scenarios, along with the numeric value added prioritization scores. For example, the measures *vegetated features (a_2)*, and *levees (a_{10})* are ranked as first priority under the baseline assessment with value added scores of twenty-two. Under the scenario, *high LRSL*, vegetated features, drops to eight with a value added score of six while the non-structural measures such as *floodplain policy and management (a_6), floodproofing and impact reduction (a_7), flood warning and preparedness (a_8),* and *relocation (a_9)*, rise in importance. Figure 0-1 presents a visual display of the ordinal ranking sensitivities of the measures to the scenarios of emergent conditions. The diamond represents the baseline ranking for the measures and the range bars extend to the highest and lowest ranking value that the measure received.

As discussed in Chapter 3 there are several metrics for determining the robustness of initiatives. Table 0-7 shows three metrics for measuring the robustness of initiatives. In two metrics, the initiative a_{10} levees is considered most robust. In one metric a_7 floodproofing and impact reduction is considered the most robust. Table 0-8 shows two metrics for measuring the influence of scenarios. Notice that s_5 severe storm is the most influential scenario using the sum of squared ranking metric. Table 0-9 summarizes the key results for this frame of priority setting for the case study.

Table 0-6 *Individual measures* time frame - the top table represents the ranking of initiatives, $r_{i,j}$. The bottom table represents the value score of initiatives, $V_j(a_i)$.

	Initiatives													
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
	Ranking of Initiatives													
Baseline	7th	**1st**	7th	12th	11th	3rd	7th	10th	3rd	**1st**	3rd	3rd	14th	13th
s_1. High LRSL	11th	8th	11th	10th	7th	**1st**	3rd	4th	2nd	5th	6th	9th	14th	13th
s_2. Coastal migration	9th	6th	9th	14th	12th	**1st**	3rd	4th	2nd	6th	8th	5th	13th	11th
s_3. Temperatures rise	7th	4th	7th	12th	11th	**1st**	7th	10th	1st	4th	1st	6th	14th	13th
s_4. Precipitation increase	9th	2nd	9th	5th	4th	6th	9th	12th	6th	**1st**	6th	3rd	14th	13th
s_5. Severe Storm	5th	4th	5th	10th	9th	12th	8th	3rd	12th	**1st**	2nd	7th	14th	11th
	Value Score of Initiatives													
Baseline	16	**22**	16	10	12	18	16	14	18	**22**	18	18	4	8
s_1. High LRSL	4	6	4	5	7	**44**	26	21	31	19	8	5	1	2
s_2. Coastal migration	6	9	6	4	5	**44**	25	24	26	9	7	12	5	6
s_3. Temperature rise	8	11	8	5	6	**33**	8	7	33	11	33	9	2	4
s_4. Precipitation increase	7	28	7	17	24	7	7	6	7	**28**	7	27	2	3
s_5. Severe storm	22	23	22	13	14	4	15	25	4	**34**	26	15	1	9

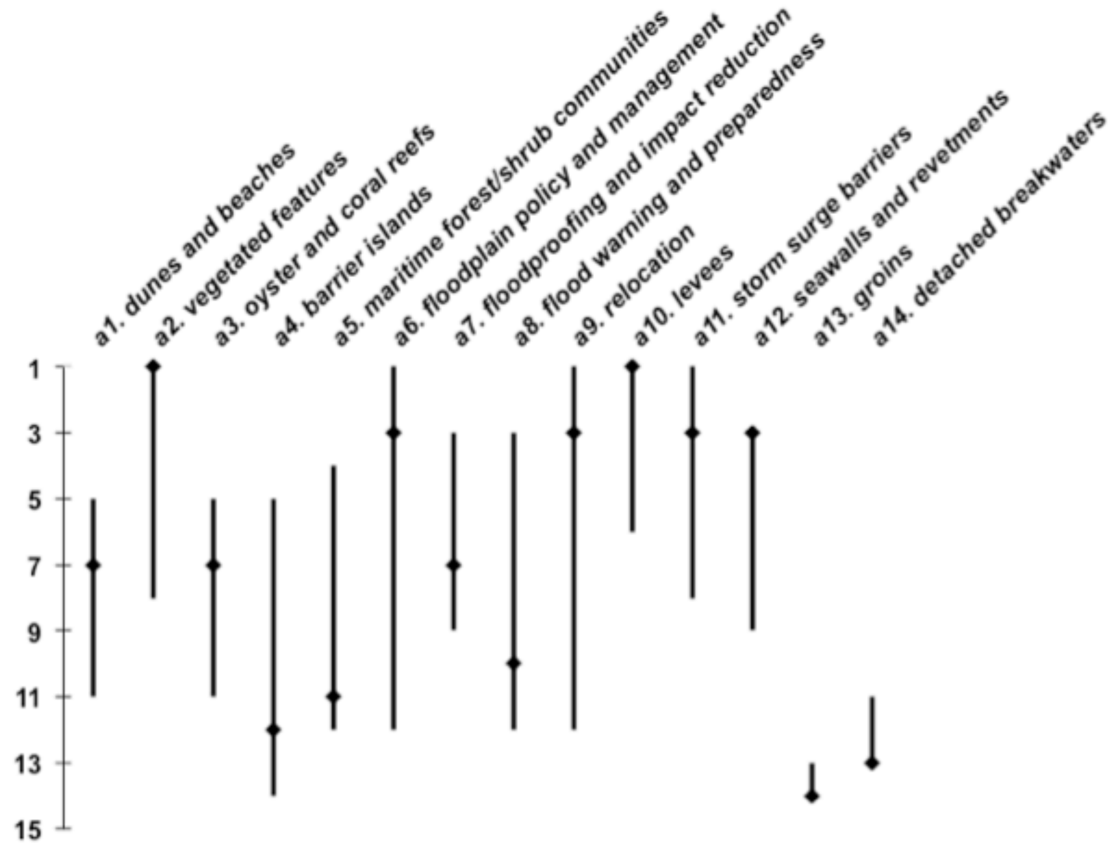

Figure 0-1: *Individual measures* time frame - sensitivity of ranking of initiatives across scenarios, $r_{i,j}$. The diamond represents the baseline ranking.

Table 0-7: ***Individual measures*** **time frame – three metrics for measuring the robustness of initiatives.**

Initiative	**Maximum ranking across scenarios (Robust initiatives min-max ranking)**	**Maximum regret (Robust initiatives minimize regret)**	**Number scenarios where initiative is in top seven priority (Robust initiative is maximum)**
a_1. Dunes and beaches	11	0.91	2
a_2. Vegetated features	8	0.86	5
a_3. Oyster and coral reefs	11	0.91	3
a_4. Barrier islands	14	0.91	1
a_5. Maritime forest/shrub communities	12	0.87	2
a_6. Floodplain policy and management	12	0.88	5
a_7. Floodproofing and impact reduction	9	**0.76**	4
a_8. Flood warning and preparedness	12	0.79	3
a_9. Relocation	12	0.88	5
a_{10}. Levees	**6**	0.80	**6**
a_{11}. Storm surge barriers	8	0.84	5
a_{12}. Seawalls and revetments	9	0.89	5
a_{13}. Groins	14	0.98	0
a_{14}. Detached breakwaters	13	0.95	0

Table 0-8: *Individual measures* time frame – two metrics to measure the influence of scenarios on energy security initiatives. The most influential scenario under each metric is highlighted in bold.

Scenario	Sum of square ranking changes relative to baseline	Percent change to top seven prioritized initiatives relative to baseline
s_1. High LRSL	0.24	**57%**
s_2. Coastal migration	0.17	43%
s_3. Temperature rise	0.04	0%
s_4. Precipitation increase	0.16	43%
s_5. Severe storm	**0.28**	43%

Table 0-9: *Individual measures* time frame - summary of key intermediate results of the scenario analysis

Type of Result	Description
Robust initiative	The initiative ***levees (a_{10})*** is the most robust. It is highly prioritized in the baseline scenario and remains in the top six priority for all scenarios.
Nearly robust initiatives	The initiative ***vegetated features (a_2)*** is nearly robust because it remains in the top six priority for all scenarios except *High LRSL* scenario
Influential scenarios	*The* ***severe storms*** *and* ***high LRSL*** scenarios provide the most changes to prioritization of initiatives based on the sum of square ranking changes of the ranking values in comparison to the *baseline* ranking
Scenarios that change the top priorities relative to baseline	The scenarios ***high LRSL, coastal migration, precipitation increase, and severe storm*** all contribute to the large changes in the top five prioritized initiatives. In these scenario, three to four of the top five initiatives from the baseline scenario fall out of the top seven priority.
Scenarios that decrease initiatives in priority relative to baseline	*The* ***severe storms scenario*** creates the most negative in changes in prioritization compared to the baseline.
Scenarios that increase initiatives in priority relative to baseline	*The* ***participation increase scenario*** and ***severe storm*** scenario creates the most positive changes in in prioritization compared to the baseline.
Initiatives that fall in priority relative to the baseline scenario	The initiative ***floodplain policy and management (a_6)*** *and* ***relocation (a_9)*** decreases in priority from third in the *baseline scenario* to twelfth in the *severe storm scenario*.
Initiatives that rise in priority relative to the baseline scenario	The initiative ***barrier islands (a_3)*** increases in priority from twelfth in the *baseline scenario* to fifth in the *precipitation increase scenario*. The initiative ***maritime forest/shrub communities (a_5)*** increases in priority from eleventh in the *baseline* scenario to fourth in the *precipitation increase scenario*. The initiative ***flood proofing and impact reduction (a_7)*** is ranked tenth in the *baseline scenario* and third in the *severe storm scenario*.

5.3.5 Reframing for Subsequent Time Frames

The results of the first frame can be used to revise the input into subsequent frames. A very robust initiative in the first frame and a_{10} *levees* and a nearly robust initiative is a_2 *vegetated features.* The initiative a_6 *floodplain policy and management* is highly prioritized in all but the *severe storm* scenario where the structural and nature-based features become more important. Non-structural features such as *flood warning and preparedness* and *floodproofing and impact reduction* became higher priorities in the *severe storm* scenario.

In the individual measures frame, the initiatives were evaluated for their properties that are general across all potential sites for implementation. In reality, the individual measures will be formed in to projects for specific sites. At the project evaluation stage of coastal infrastructure systems engineering, the criteria used to evaluate the set of initiatives should be revised to be more specific, including consideration of the economic benefits, environmental quality, and other social effects of each initiative. Thus the second frame will evaluate project initiatives for a specific coastal region in the southeastern part of the United States.

Table 0-10: *Individual measures* time frame - reporting of criteria, initiatives, scenarios, intermediate output and reframing of scenario-based preference model

Input	Output	Reframing Questions	Reframing
Fourteen Initiatives *Dunes and beaches* *Vegetated features* *Oyster and coral reefs* *Barrier islands* *Maritime forest/shrub communities* *Floodplain policy and management* *Floodproofing and impact reduction* *Flood warning and preparedness* *Relocation* *Levees* *Storm surge barriers* *Seawalls and revetments* *Groins* *Detached breakwaters*	**One robust initiatives** *levees* **Two nearly robust initiatives** *vegetated features* *floodplain policy and management*	The individual initiatives can be revised into specific projects for specific location.	Individual measures reformed into projects. **Two nature-based initiatives revised** *Dunes and vegetation* *Beach nourishment* **Four non-structural initiatives revised** *Establish a no-growth program* *Buyout and land acquisition* *Relocation of structures* *Relocate state highway* **Four structural initiatives revised** *Seawalls* *Revetments* *Sand covered soft structures* *Groins*
Seventeen Criteria *Breaking of offshore waves* *Wave attenuation* *Slow inland water transfer* *Increased infiltration*		The criteria used to evaluate the next set of initiatives can be revised to be more specific about the economic benefits, environmental quality, and	**All criteria revised**

Reduce erosion *Improve/control floodplain development* *Reduce opportunity for damages* *Improve natural coast environment* *Increase community resilience* *Do not increase flood potential elsewhere* *Improve public awareness/responsibility* *Surge attenuation* *Reduce flooding* *Risk reduction for vulnerable areas* *Reduce wave overtopping* *Shoreline stabilization behind structure* *Reduce salinity intrusion*		other social effects of each initiative	
Five Scenarios *High LRSL* *Coastal migration* *Temperature rise* *Precipitation increase* *Severe storm*	**Two influential scenarios** *severe storms and high LRSL*	Recommended for a future frame	**Five scenarios maintained**

5.4 Second Time Frame – Project Priorities for Coastal Risk Reduction and Resilience

5.4.1 Overview

The second time frame (I^2) – project priorities frame for coastal risk reduction - is similar to the individual measures frame (I^1) in that it is priority setting to reduce coastal risk and increase resilience of coastal regions. The second frame uses scenario-based multi-criteria analysis to prioritize flood risk and storm damage reduction projects for a southeastern area of the United States. It is different from the first stage in that it focuses on a specific region.

5.4 2. Baseline Analysis

The initiatives to be prioritized are nature, nature-based, nonstructural, and structural measures from the individual measures frame (I^1) formed in to projects. Table 0-11 provides a list of the initiatives used in this demonstration. The criteria were derived from the USACE planning considerations: National Economic Development (NED), Environmental Quality, other Social Effects, and Regional Economic Development. Table 0-12 provides the value score $v_k(a_i) = v_k(z_i^k)$ for each initiative evaluated on each criterion. The baseline assessment assumes equal weights for each criterion. Table 0-13 displays the baseline value score, $V_0(a_i)$, and associated ranking for each initiative.

Table 0-11: ***Project priorities*** **time frame – set A={a_1,...,a_N} of coastal project initiatives to be prioritized**

a_1 No action
a_2 Establish a no-growth program
a_3 Relocation of structures
a_4 Relocate state highway
a_5 Buyout and land acquisition
a_6 Seawalls
a_7 Revetments
a_8 Sand covered soft structures
a_9 Beach nourishment
a_{10} Groins
a_{11} Dunes and vegetation

Table 0-12: *Project priorities* time frame – Likert type assessment of initiatives across criteria, $v_k(a_i)$

		Initiatives										
	Criteria	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
Net Economic Development	z_1. Increase inundation reduction benefit	0.33	0	0.33	0.33	0.33	0	0.33	0.33	1	0	1
	z_2. Reduce costs	0.33	0.33	0.33	0	0.33	0	0.33	0.66	1	0.66	1
Environmental Quality	z_3. Protect dune habitat	0.33	0.33	0.33	0.33	0.33	0.33	0.66	0	1	0	1
	z_4. Protect wildlife habitat	0.33	0	0	0	0.33	0.33	0.33	0.33	0.66	0.66	0.66
Other Social Effects	z_5. Maintain support of community	0.33	0	0	0	0.33	0.33	0.66	0.66	0	0	0
	z_6. Increase aesthetics	0.33	0	0	0	0.33	0	0.33	0.66	0.66	0	0.66
	z_7. Protect property values	1	0.66		0.33	0	0	0	0.66	1	0	1
	z_8. Protect evacuation routes	0	0	0	0	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	z_9. Protect recreation areas	0	0	0	0	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	z_{10}. Minimize conflict with other land use laws	0.33	0.33	0.33	0.33	0	0	0.33	1	1	0.33	1
Regional Economic Development	z_{11}. Protect regional property values	0.33		0.33	0.33	0.33	0	0.33	0.33	1	0	1
	z_{12}. Maintain tax value	0.33	0.33	0.33	0	0.33	0	0.33	0.66	1	0.66	1
	z_{13}. Maintain tourism industry	0.33	0.33	0.33	0.33	0.33	0.33	0.66	0	1	0	1

Table 0-13: *Project priorities* time frame - the baseline value function scores and associated rankings for the eleven initiatives.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
Baseline value score	33	21	15	21	26	28	44	51	**72**	26	**72**
Baseline ranking	5th	9th	11th	9th	7th	6th	4th	3rd	**1st**	7th	**1st**

5.4.3 Details of the Scenario-Based Preference Analysis

Next, a set of scenarios S={s_0, s_1,…,s_5} that are combinations of emergent/future conditions are identified. The same five scenarios used in the first frame are included in this frame*: s_1. high LRSL; s_2. coastal migration; s_3. temperature rise; s_4; precipitation increase; and s_5. severe storms*. The criteria are reevaluated for each of the scenarios described in section 2. These adjustments answer the following question: "Compared to a baseline scenario, which of the criteria becomes more important or less important under scenario s_k?" The answer to the question is categorized as a major decrease in importance, minor decrease in importance, minor increase in importance, or major increase in importance. Table 0-14 shows the adjusted priority of the criteria under considered stakeholder scenarios. For example, under the stakeholder scenario, *s_1, High LRSL*, there is a major increase in the importance of the criteria increase inundation reduction benefit, protect dune habitat, and maintain support of community. If λ_k increases under scenario s_j compared to the baseline scenario the coefficient of this criterion is adjusted through defining a constant α >1 and multiplying the baseline coefficient λ_k by α. A new non-normalized coefficient for the k^{th} criterion is then

$$\lambda'_k = \alpha \times \lambda_k.$$

The set of constant multipliers are defined for this case study are {1/9, 1/3, 1, 3,9}, where a major decrease corresponds to a multiplier of 1/9, a minor decrease corresponds to a multiplier of 1/3, no change corresponds to a multiplier of 1, a minor increase corresponds to a multiplier of 3 and a major increase corresponds to a multiplier of 9. The new set of λ'_k are then normalized to sum to one. **Table 0-15** describes the normalized adjusted weight for each criterion in each scenario. These coefficients were then used with the value scores of **Table 0-12** to produce a value score for each initiative under each scenario using the equation:

$$\mathbf{V_j(a_i) = 100 * \sum_{k=1}^{K} \lambda_{j,k}\, v_k(a_i), \text{ with } \sum_{k=1}^{K} \lambda_{j,k} = 1 \text{ and } 0 \le v_k(a_i) \le 1}$$

for all k = 1,…,K; i= 1,…N

Table 0-14: *Project priorities* time frame - elicitation of incremental adjustments of importance of criteria across the five scenarios

Criteria	Scenarios				
	s_1 High LRSL	s_2 Coastal migration	s_3 Temperature rise	s_4 Precipitation increase	s_5 Severe storms
z_1. Increase inundation reduction benefit	MAJOR INCREASE			MAJOR INCREASE	MAJOR INCREASE
z_2. Reduce costs					
z_3. Protect dune habitat	MAJOR DECREASE			MAJOR INCREASE	
z_4. Protect wildlife habitat			MAJOR INCREASE		
z_5. Maintain support of community	MAJOR INCREASE				
z_6. Increase aesthetics					
z_7. Protect property values					
z_8. Protect evacuation routes					MAJOR INCREASE
z_9. Protect recreation areas		MAJOR INCREASE			
z_{10}. Minimize conflict w/other land use laws					
z_{11}. Protect regional property values		minor decrease			
z_{12}. Maintain tax value		MAJOR INCREASE			
z_{13}. Maintain tourism industry		MAJOR INCREASE			

Table 0-15: *Project priorities* time frame - corresponding normalized adjusted criteria coefficient expressed as a percentage for each criterion in each scenario (including baseline)

Criteria	Baseline	s_1 High LRSL	s_2 Coastal migration	s_3 Temperature rise	s_4 Precipitation increase	s_5 Severe storms
z_1. Increase inundation reduction benefit	7.69%	32.02%	2.75%	4.76%	31.03%	31.03%
z_2. Reduce costs	7.69%	3.56%	2.75%	4.76%	3.45%	3.45%
z_3. Protect dune habitat	7.69%	0.40%	2.75%	4.76%	31.03%	3.45%
z_4. Protect wildlife habitat	7.69%	3.56%	2.75%	42.86%	3.45%	3.45%
z_5. Maintain support of community	7.69%	32.02%	2.75%	4.76%	3.45%	3.45%
z_6. Increase aesthetics	7.69%	3.56%	2.75%	4.76%	3.45%	3.45%
z_7. Protect property values	7.69%	3.56%	2.75%	4.76%	3.45%	3.45%
z_8. Protect evacuation routes	7.69%	3.56%	2.75%	4.76%	3.45%	31.03%
z_9. Protect recreation areas	7.69%	3.56%	24.77%	4.76%	3.45%	3.45%
z_{10}. Minimize conflict with other land use laws	7.69%	3.56%	2.75%	4.76%	3.45%	3.45%
z_{11}. Protect regional property values	7.69%	3.56%	0.92%	4.76%	3.45%	3.45%
z_{12}. Maintain tax value	7.69%	3.56%	24.77%	4.76%	3.45%	3.45%
z_{13}. Maintain tourism industry	7.69%	3.56%	24.77%	4.76%	3.45%	3.45%

5.4.4 Output from project priorities time frame

Table 0-16 shows the results of applying the scenario-based preference analysis. The table describes the measures ranked across the baseline and five scenarios described above, along with the numeric value added prioritization scores. For example, the initiative *dunes and vegetation* (a_{11}) and *beach nourishment* (a_9) are first priority under the baseline assessment with value added scores of seventy-two. Both of these remain top priority under all but the *severe storm* scenario. Figure 0-2 presents a visual display of the ordinal ranking sensitivities of the initiatives to the scenarios of emergent conditions. The diamond represents the baseline ranking for the initiative and the range bars extend to the highest and lowest ranking value that the initiative received. The most influential scenario as defined by $m(s_j)$ is s_4 *precipitation increase* followed by s_4, *severe storm* and s_1 *high LSLR.* Table 0-19 describes the key intermediate results from the project priorities frame.

As discussed in Chapter 3 there are several metrics for determining the robustness of initiatives. Table 0-18 shows three metrics for measuring the robustness of initiatives. In all three metrics, the initiative a_9 *beach nourishment* and a_{11} *dunes and vegetation* are considered the most robust. Table 0-18 shows two metrics for measuring the influence of scenarios. Notice that s_4 *precipitation increase* is the most influential scenario using the sum of squared ranking metric. Table 0-19 summarizes the key results for this frame of priority setting for the case study.

Table 0-16: *Project priorities* time frame - the top table represents the ranking of initiatives, $r_{i,j}$. The bottom table represents the value score of initiatives, $V_j(a_i)$.

	Initiatives										
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
	Ranking of Initiatives										
Baseline	5th	9th	11th	9th	7th	6th	4th	3rd	**1st**	7th	**1st**
s_1. High LRSL	10th	8th	9th	11th	7th	5th	4th	3rd	**1st**	6th	**1st**
s_2. Coastal migration	5th	9th	11th	9th	6th	8th	4th	3rd	**1st**	6th	**1st**
s_3. Temperature rise	5th	11th	8th	7th	6th	9th	4th	3rd	**1st**	10th	**1st**
s_4. Precipitation increase	9th	11th	8th	7th	6th	5th	3rd	4th	**1st**	10th	**1st**
s_5. Severe storm	7th	9th	11th	10th	6th	3rd	**1st**	2nd	4th	8th	4th
	Value Score of Initiatives										
Baseline	33	21	15	21	26	28	44	51	72	26	72
s_1. High LRSL	24	28	25	18	30	40	57	61	68	40	68
s_2. Coastal migration	27	15	13	15	23	17	37	62	69	23	69
s_3. Temperature rise	33	13	22	25	29	17	40	44	83	16	83
s_4. Precipitation increase	24	18	25	28	30	49	56	51	69	21	69
s_5. Severe storm	24	18	16	18	30	49	66	60	41	21	41

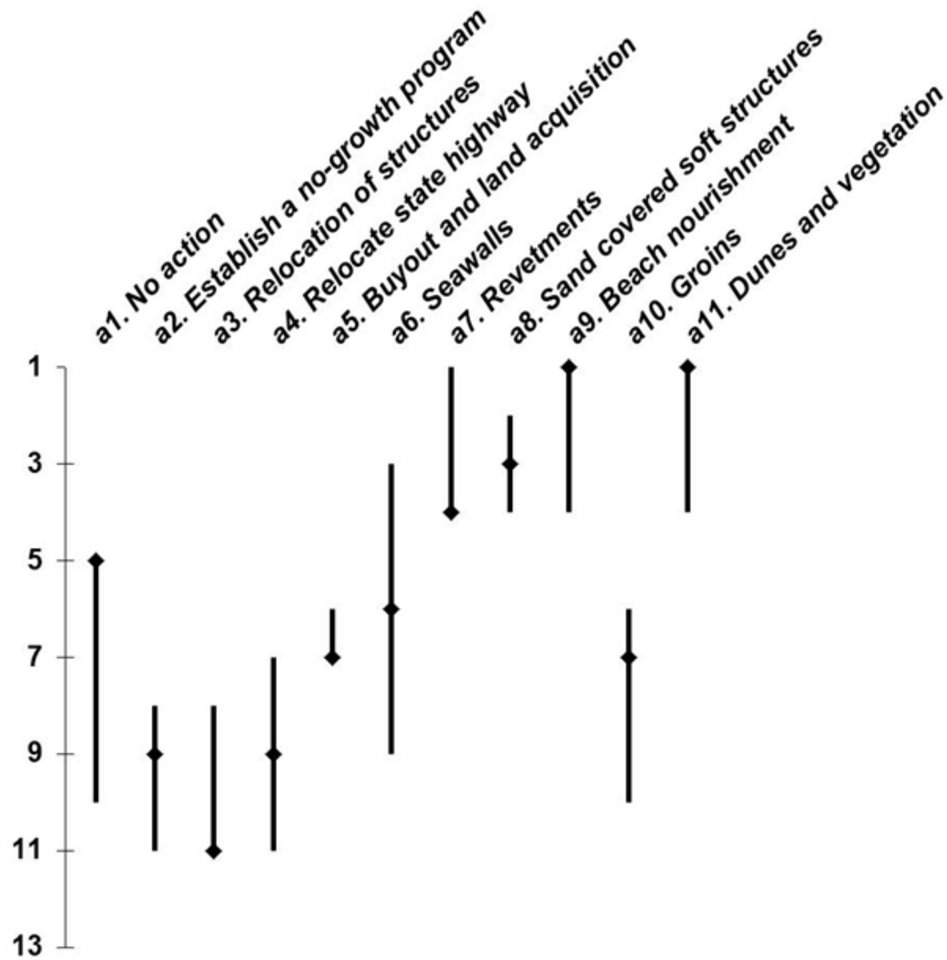

Figure 0-2: *Project priorities* time frame – sensitivity of ranking of initiatives across scenarios, $r_{i,j}$. The diamond represents the baseline ranking.

Table 0-17: *Project priorities* time frame – three metrics for measuring the robustness of initiatives.

Initiative	Maximum ranking across scenarios (Robust initiatives min-max ranking)	Maximum regret (Robust initiatives minimize regret)	Number scenarios where initiative is in top five priority (Robust initiative is maximum)
a_1 No action	10th	0.65	3
a_2 Establish a no-growth program	11th	0.84	0
a_3 Relocation of structures	11th	0.81	0
a_4 Relocate state highway	11th	0.78	0
a_5 Buyout and land acquisition	7th	0.67	0
a_6 Seawalls	9th	0.80	3
a_7 Revetments	**4th**	0.52	6
a_8 Sand covered soft structures	**4th**	0.47	**6**
a_9 Beach nourishment	**4th**	**0.38**	**6**
a_{10} Groins	10th	0.81	0
a_{11} Dunes and vegetation	**4th**	**0.38**	**6**

Table 0-18: *Project priorities* time frame – two metrics to measure the influence of scenarios.

Scenario	Normalized sum of square ranking changes	Percent change to top five prioritized initiatives relative to baseline
s_1. High LRSL	0.082	**20%**
s_2. Coastal migration	0.014	**0%**
s_3. Temperature rise	0.082	**0%**
s_4. Precipitation increase	**0.105**	**20%**
s_5. Severe storm	0.100	**0**

Table 0-19: *Project priorities* time frame - summary of key intermediate results of the scenario analysis

Type of Result	Description
Robust initiative	The initiatives ***beach nourishment (a_9)***, ***dunes and vegetation (a_{11}), a_8 sand covered soft structures,*** and ***a_{11} dunes and vegetation*** are the most robust initiatives. They remain in the top five priority in all scenarios and have the minimum maximum regret across scenarios.
Nearly robust initiatives	N/A
Influential scenarios	*The* ***precipitation increase*** scenario provides the most changes to prioritization of initiatives based on the sum of square ranking changes of the ranking values in comparison to the baseline ranking. The ***severe storm*** scenario provides the second largest changes to prioritization.
Scenarios that change the top priorities relative to baseline	*The* ***precipitation increase*** *and* ***high LRSL change*** *one of the top five prioritized initiatives compared to the baseline.*
Scenarios that decrease initiatives in priority relative to baseline	*The* ***high LRSL*** creates the most negative change in rankings overall. It decreases the initiative ***do nothing (a_1)*** from fifth priority to tenth.
Scenarios that increase initiatives in priority relative to baseline	*The* ***severe storm***, ***precipitation increase, and temperature rise*** scenarios create the most positive change in rankings overall. *Severe store* scenario increases the initiative ***a_7 revetments*** from fourth priority to firs and the initiative *a_6 seawalls* from sixth priority to third priority. The *precipitation increase* and *temperature rise* scenario increases the initiative *a_3 relocation of structures* from eleventh priority to eighth.
Initiatives that increase in priority relative to the baseline scenario	The initiative ***do nothing (a_1)*** decreases in priority from fifth in the *baseline scenario* to tenth in the *high LRSL scenario.*
Initiatives that increase in priority relative to the baseline scenario	The initiative ***a_7 revetments*** increases from fourth priority to first and the initiative ***a_6 seawalls*** from sixth priority to third priority in the *severe storm* scenario. The initiative *a_3 relocation of structures* increase from eleventh priority to eighth in the *precipitation increase* and *temperature rise* scenarios.

5.4.5 Reframing for Subsequent Time Frames

In the project priorities frame, the scenarios *precipitation increase*, *severe storm*, and *high LSLR* were identified as the most influential scenarios. A subsequent frame could explore combinations of severe storm and high LSLR and scenarios with other conditions. For example, the next five scenarios in the third demonstration could include combinations of increase in storm intensity, and/or storm frequency with erosion, high LSLR, dune crest height threshold overcome, and higher high tide events. In this second frame the initiatives to be selected for further study will be those that were most robust against scenarios. These include *beach nourishment*, *dunes and vegetation*, *sand covered soft structures*, and *revetments*. The next frame should explore criteria such as sea-level threshold. The initiatives *beach nourishment* and *dunes and vegetation* could be combined with *sand covered soft structures*, and *revetments* to improve the risk reduction and resilience in the severe storm scenario (Table 0-20).

Table 0-20: *Project priorities* time frame - reporting of criteria, initiatives, scenarios intermediate results and reframing of scenario-based preference model

Input	Output	Reframing Questions	Reframing
Eleven Initiatives *No action* *Establish a no-growth program* *Relocation of structures* *Relocate state highway* *Buyout and land acquisition* *Seawalls* *Revetments* *Sand covered soft structures* *Beach nourishment* *Groins* *Dunes and vegetation*	**Four robust initiatives** *Revetments* *Sand covered soft structures* *Beach nourishment* *Dunes and vegetation*	The initiatives beach nourishment and dunes and vegetation be combined with revetments and sand covered soft structures	*Recommended for subsequent frame*
Thirteen Criteria *Increase inundation reduction benefit* *Reduce costs* *Protect dune habitat* *Protect wildlife habitat* *Maintain support of community* *Increase aesthetics* *Protect property values* *Protect evacuation routes* *Protect recreation areas* *Minimize conflict with other land use laws*		Revised criteria could include sea-level threshold, reversibility of project, adaptability, etc.	*Recommended for subsequent frame*

Protect regional property values *Maintain tax value* *Maintain tourism industry*			
Five Scenarios *High LRSL* *Coastal migration* *Temperature rise* *Precipitation increase* *Severe storm*	**Three influential scenarios** *precipitation increase*, *severe storm*, and *high LSLR*	Recommend combinations of increase in storm intensity, and/or storm frequency with erosion, high LSLR, dune crest height threshold overcome, and higher high tide events.	*Recommended for subsequent frame*

5.6 Discussion of Evolution across Time Frames

This case study has presented two frames for priority setting for uncertainties of climate and other factors influencing priorities for coastal infrastructure systems. The first time involved priority setting for coastal mitigation and adaption initiatives. The second time frame evolved the first by different criteria suitable to a feasibility evaluation of projects for a particular location in the southeastern coast of the United States. The scenarios that most disrupted the prioritization order of initiatives in each of the both frames were *increase in severe storms* and *high LSLR*. Some of the specific evolution includes:

- Two nature-based initiatives revised
- Four non-structural initiatives revised
- Four structural initiatives revised
- All criteria revised
- Identification of two influential scenarios that should be the subject of further detailed analysis.

The two time frames presented in the case study are an initial attempt at putting climate change and other scenarios in context of decision making for coastal infrastructure development and are rather generic in their application. The selection of criteria, initiatives, and scenarios should be revised as more location specific problems are identified.

5.6 Chapter Summary

In summary, there is an urgent need to know the influence of climate and other uncertainties to R&D priorities of industry, government, and the military. This case study has presented two time frames of priority setting for uncertainties of climate. The first time frame involved priority setting for individual measures for coastal risk and resilience initiatives. The second time frame evolved the first by combining individual measures into projects and evolving the criteria to that which is typical of coastal project evaluations.

: Discussion

6.1 Chapter Overview

This chapter will provide a discussion of the above-developed methods for scenario-based preferences for risk analysis in multiple time frames. First it will discuss validation of the methods. Second it will discuss the issues and limitations of the methods.

6.2 Validation

The validation of decision analysis frameworks has several challenges. Shilling et al. (2007) discuss three categories of effectiveness metrics: process effectiveness, output effectiveness and outcome effectiveness to evaluate the effect of decision analyses in organizations.

Process effectiveness metrics assess the quality of the decision process. The competing value framework (Quinn and Rohrbaugh 1981, 1983; McCartt and Rohrbaugh 1995; Rohrbaugh 2005) rates a decision to be effective if it includes adequate information (empirical perspective), clear thinking about this information (rational perspective), flexibility and creativity in the process (political perspective), and sufficient participation (consensual perspective). Matheson and Matheson (1998) outline a "decision quality chain:" to choose the appropriate frame, to search for creative, workable alternatives, to use meaningful and reliable information, to make clear value trade- offs, to use logically correct reasoning, and to try to achieve commitment to action. Based on this quality chain, Matheson and Matheson (2001) suggest measuring the decision quality of organizational units on dimensions such as value-creation culture, creating alternatives, open-information flow, embracing uncertainty, and system thinking. Further decision process measures include information processing criteria, such as the numbers of attributes used (Timmermans and Vlek 1994), social interaction criteria, e.g., the ease of expression of opinions (Timmermans and Vlek 1996), and the quality of the communication, teamwork, or discussion (Davison 1997, 1999). Shilling et al (2007) suggests evaluating decision analysis models against eight dimensions: participation, Strategic insight, Top-down vs. bottom up, Quantity of information exchange, transparency,

Table 0-1 shows a questionnaire that can be distributed after the modeling process. It can be distributed after the first frame and again after the final frame to compare results. These questions address eight dimensions and are modified versions of those used in Shilling et al. (2007) and Ram and Montibeller (2013).

Output effectiveness metrics capture the quality of the immediate output of the model. These include attitudinal surveys, expected value calculations, and alignment measures. Attitude surveys are the most common analysis of the output quality of decision analyses, for example, asking decision makers for their satisfaction with the final model (Timmermans and Vlek 1996, Finlay and Forghani 1998). Clemen and Kwit (2001) proposed a more quantitative approach, using field data from decision analyses applied over a period of 10 years at Eastman Kodak. Based on expected net present value calculations, the authors analyzed the value of decision analyses by comparing the expected value of the strategy, recommended by the decision analysis, to the expected value of the company's "momentum strategies"—the organization's preferred course of action without the analysis. Other output benefits of decision modeling including the provision of a common language to discuss complex issues, a joint understanding of the issues at hand, a sense of common purpose, and a possible alignment of stakeholders to the joint way forward (Clemen and Kwit 2001, Phillips 2007, Phillips and Bana e Costa 2007). Table 0-2 shows an example of an output effectiveness survey that could be distributed to stakeholders after several time frame of scenario-based preference modeling. These questions assess the effectiveness of the process to discover new initiatives, new criteria, or new scenarios.

Outcome effectiveness metrics focus on the assessment of the extent to which executing the model output assists in achieving the final objectives of the decision makers. The measurement of decision aids in field settings is usually difficult to analyze. Macmillan (2000) is one of the few studies that attempted to do this. Macmillan (2000) compared organizational performance measures for the upstream gas industry in the United Kingdom at one point in time to the degree of sophistication of decision analyses applied. Performance measures included return on equity, financial analysts' company valuations, or price-earning ratios. Her study established a positive relationship between a high degree of sophistication of decision analysis in companies and several performance indicators. Other researchers have focused on simulation environments to analyze the impact of decision aids on profit, net worth, net earnings and other financial indicators (Lilien et al. 2004; Webby and O'Connor 1994; Sharda et al. 1988).

Appendix C shows a completed process and output validation survey filled out by a stakeholder from the USACE who participated in the case study on climate change and coastal infrastructure.

Table 0-1: Example process effectiveness questionnaire

1. Extent of participation by people in your organization in the problem solving process	Not very participatory, including few opinions within the organization	1	2	3	4	5	6	7	Very participatory, including a variety of opinions within the organization
(a) Scenario-based Preferences in Multiple Time Frames: How participatory do you rate the decision analysis process?									
(b) Ideal: How participatory should similar problems ideally be solved in your organization?									
(c) Status Quo: How participatory would similar problems have been solved with the existing processes/methods									
2. Extent of top-down versus bottom-up influence in your organization during problem-solving processes	Strongly top-down driven (mainly decided by top-level management) organization	1	2	3	4	5	6	7	Strongly "bottom-up" (including middle management influenced)
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									

		1	2	3	4	5	6	7	
3. Extent of transparency and comprehensibility	Complex, not very transparent and comprehensible	1	2	3	4	5	6	7	Highly transparent and comprehensible
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									
4. Contribution of rational analysis and intuitive judgment	Mostly based on intuitive decision making	1	2	3	4	5	6	7	Mostly based on rational analysis
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									
5. Extent to which creativity or traditional ideas contribute to problem-solving	Less creativity-simulating, more based on "established" ideas	1	2	3	4	5	6	7	Highly creativity stimulating, less based on "established" ideas
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									

		1	2	3	4	5	6	7	
6. Extent of interactivity and dialogue-orientation (“Quality” of information flow)	Less interactive and less dialogue-oriented	1	2	3	4	5	6	7	Interactive and dialogue-oriented
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									
7. Extent of information exchange (Quantity of information flow between different stakeholders)	Little exchange of information	1	2	3	4	5	6	7	Extensive exchange of information
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									
8. Extent of strategic insights	Strategic priorities not challenged, focus on an optimal solution	1	2	3	4	5	6	7	Strategic priorities challenged, focus on a robust solution
(a) Scenario-based Preferences in Multiple Time Frames									
(b) Ideal									
(c) Status Quo									

Table 0-2: Example of outcome effectiveness stakeholder survey

1. Extent of criteria identification How do you rate the decision analysis process in terms of identifying new criteria not previously identified?	No new criteria were identified	1	2	3	4	5	6	7	New criteria were identified
2. Extent of initiative identification How do you rate the decision analysis process in terms of identifying new initiatives not previously identified?	No new initiatives were identified	1	2	3	4	5	6	7	New initiatives were identified
3. Extent of scenario identification How do you rate the decision analysis process in terms of identifying new scenarios not previously identified?	No new scenarios were identified	1	2	3	4	5	6	7	New scenarios were identified

6.3 Issues and Limitations of the Method

There are several issues and limitations concerning the methods for implementing scenario-based preference models in multiple time frames.

The first issue concerns the implementation of the method with many stakeholders in multiple periods of engagement. The success of this process depends heavily on the quality of the stakeholder input and their ability to provide preferences and tradeoffs across criteria and scenarios. Ideally, many stakeholders should be involved; however, coordinating this exercise may prove difficult and time-consuming. Each iteration of the model may require several hours of group work with periods of investigative analysis in between. If stakeholders do not feel that the process is going to provide them with any additional insight, they may not feel the desire to provide quality information and become less and less engaged over time.

The second issue concerns the selection of criteria to measure objectives. Tversky and Kahnemans (1981) demonstrated a framing effect, which showed that though two attributes have a clear deterministic relationship, the attribute selected to describe the consequences can affect the choice of alternative. Multicriteria models assume rationality, of which invariance to irrelevant features of options is an essential aspect. Invariance is violated in framing effects such as the Asian disease problem (Tversky and Kahnemans, 1981). To address framing effect, if there are several attributes that could be used to describe the same consequences, such as lives lost verses lives saved, the facilitator should check that all attributes descriptions for the same objective result in the same preference (or weight) for that objective.

The third issue concerns anchoring on the initial set of initiatives (Keeney 1992) It is difficult to determine whether the set of initiatives chosen for evaluation is better than another. Keeney suggests as one way to overcome the tendency to anchor on a subset of inferior initiatives is to focus on one objective at a time and find an initiative that would be very desirable if that were the only objective. The anchoring tendency could be amplified during multiple frames of the scenario-based preference model. In other words, if a subset of robust initiatives is selected from the first time frame to be further prioritized, and only scenarios that affect those initiatives are considered in the next frame, this could further increase the commitment to potentially inferior initiatives. To avoid this tendency, at each iteration, stakeholders should be asked to focus on one scenario at a time and consider whether there are additional initiatives that might be very desirable if that were the only scenario. They should consider whether any scenario justifies reconsideration of initiatives that were previously discarded. It is possible that more initiatives may be created if scenarios are thought about one at a time.

A fourth, and related, issue concerns the ability of stakeholders to envision a broad set of scenarios. Again, this depends heavily on the stakeholder engagement and breadth of knowledge and experience. One approach is to ask stakeholders to individually evaluate each criterion and consider the question 'what external situations will this increase or decrease the importance of this criterion?' If the set of scenarios are not broad enough, this could lead to premature commitment to a particular initiative for further analysis.

A fifth issue is that this methodology incorporates reasoned judgment and subjectivity at each stage of the process. The ability of the stakeholders to interpret the output and then make decisions on how to proceed with the next iteration may be challenged due to bounded rationality. Kahneman (2002) discusses bounded rationality and that intuitive decisions will be shaped by the factors that determine the accessibility of different features of the situation. Highly accessible features will influence decisions, while features of low accessibility will be largely ignored. For example, just because an initiative performs poorly in one scenario, does not necessarily mean that it should be discarded. The scenario for which an initiative performs poorly may be highly unlikely, while the other scenarios that it performs well in are much more likely. Thus, it is important to note that this model should be viewed as a method for increasing dialogue, creativity, and a shared understanding of the problem space and should not be used as the sole decision tool. Furthermore, understanding how the results of this method can be misused or misinterpreted should be an area of future research.

6.4 Chapter Summary

This chapter discussed validation and issues and limitations of scenario-based preference analysis across time frames. Section 6.2 discussed process, output, and outcome validation. It provided a survey that could be handed to participants after the modeling process to measure the process and output effectiveness of the method. Section 6.3 discussed limitations of the method. Several of these limitations may be overcome with future research as discussed in the next chapter.

. Summary and Conclusions

7.1 Overview of Chapter

This chapter will summarize this dissertation. First, it will review the purpose and scope of the dissertation. Second it will discuss the research contributions. Finally, it will conclude with future work to extend the impact and relevance of this dissertation.

7.2 Review of purpose and scope

The aim of this dissertation was to specify principles for applying scenario-based preferences for risk analysis across time frames and demonstrate the process in two case studies. Chapter 2 provided a background and literature review to provide motivation for the dissertation. Chapter 3 provided the mathematical description of the methodology and recommendations for applying the methodology in practice. Chapter 4 provided a case study on energy security decision-making at military installations. Chapter 5 provided a case study on climate change planning in coastal regions. Chapter 6 provided a discussion of the model validation as well as discussion on the limitations and issues. Figure 0-2 provides a summary of the concept of scenario-based preferences in multiple time frames with corresponding sections of the dissertation that describe the methods and application in the two case studies. Figure 0-2

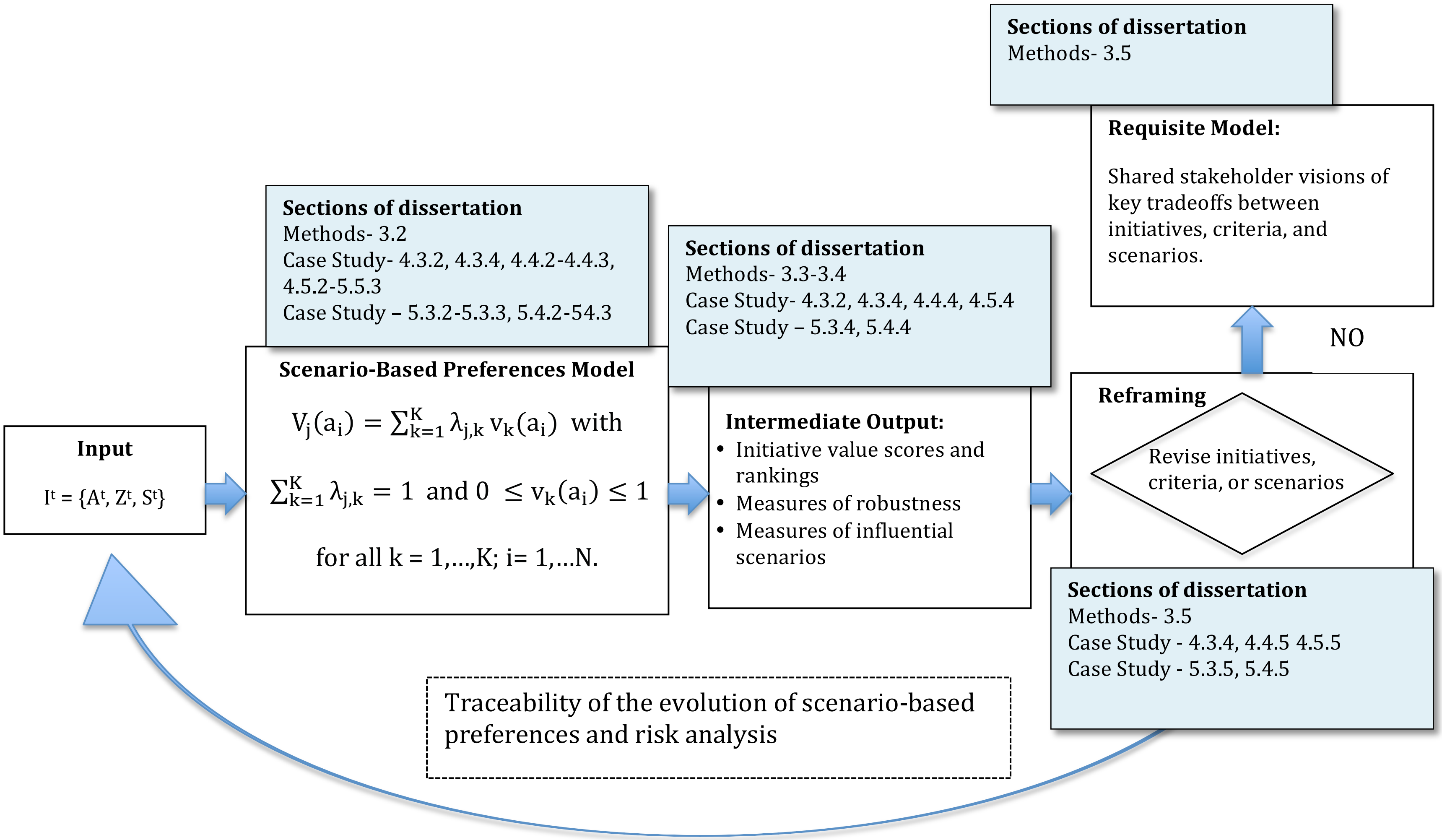

Figure 0-1: Concept and application for scenario-based preferences in multiple time frames with corresponding sections of the dissertation

7.3 Research contributions

The state of the art of scenario-based preference modeling for risk analysis is static and one-time. This dissertation has addressed this gap in the literature by providing motivation and principles for the iterative process and demonstrating the resulting process in two case studies, each providing analysis across several time frames. This dissertation contributes to the literature on scenario-based preference modeling as developed by Stewart et al. 2013; Karvetski et al 2012, 2011a, 2011b and 2011c; Schroeder and Lambert 2009; You 2013; Goodwin and Wright 2001; Montbeller et al. 2006 and Parnell 1999; as well as the literature of robust decision making, which has not previously considered robustness of decisions to scenario-based preferences.

There are several theoretical, methodological, and application contributions of this work.

Contribution 1. The first contribution is a framework for scenario-based preference modeling in multiple time frames. This includes the incorporation of scenario analysis as part of dynamic problem structuring for systems engineering and innovation

Contribution 2. The second contribution is the adoption and extension of several metrics of robustness that are necessary to guide reframing of the scenario-based preference model.

Contribution 3. The third contribution is the adoption and extension of several metrics of disruptive scenarios that are necessary to guide reframing of the scenario-based preference model.

Contribution 4. The fourth contribution is the description of qualitative and quantitative principles for refining scenarios, criteria, and initiatives across time frames. This includes a set of questions to support reframing across time frames.

Contribution 5. The fifth contribution is a prototype to record the evolution of initiatives, criteria, and scenarios across time frames to support traceability

Contribution 6. The sixth contribution is the application to a case study on energy security at military installations. The relationship of four frames of scenario-based preference analysis were discussed and developed including:

- First frame – Conceptual design frame for an installation
- Second frame – R&D frame across installations (Hamilton et al. 2013a)
- Third frame - Strategic priories for an installation (Hamilton and Lambert, 2014 submitted).
- Fourth frame – Distributed generation design frame

Contribution 7. The seventh contribution is the application case study of climate change and coastal protection (report of Hamilton, Lambert, Valverde, 2014 submitted archival paper to ASCE/ASME Journal of Risk and Uncertainty in Engineering Systems)

- First frame – Individual measures frame for coastal risk reduction and resilience

- Second frame – Project priorities frame for coastal risk reduction and resilience

Figure 0-2 provides a display of how this dissertation contributes to the recent literature on scenario-based preference analysis. Appendix D provides a timeline of activities and contributions.

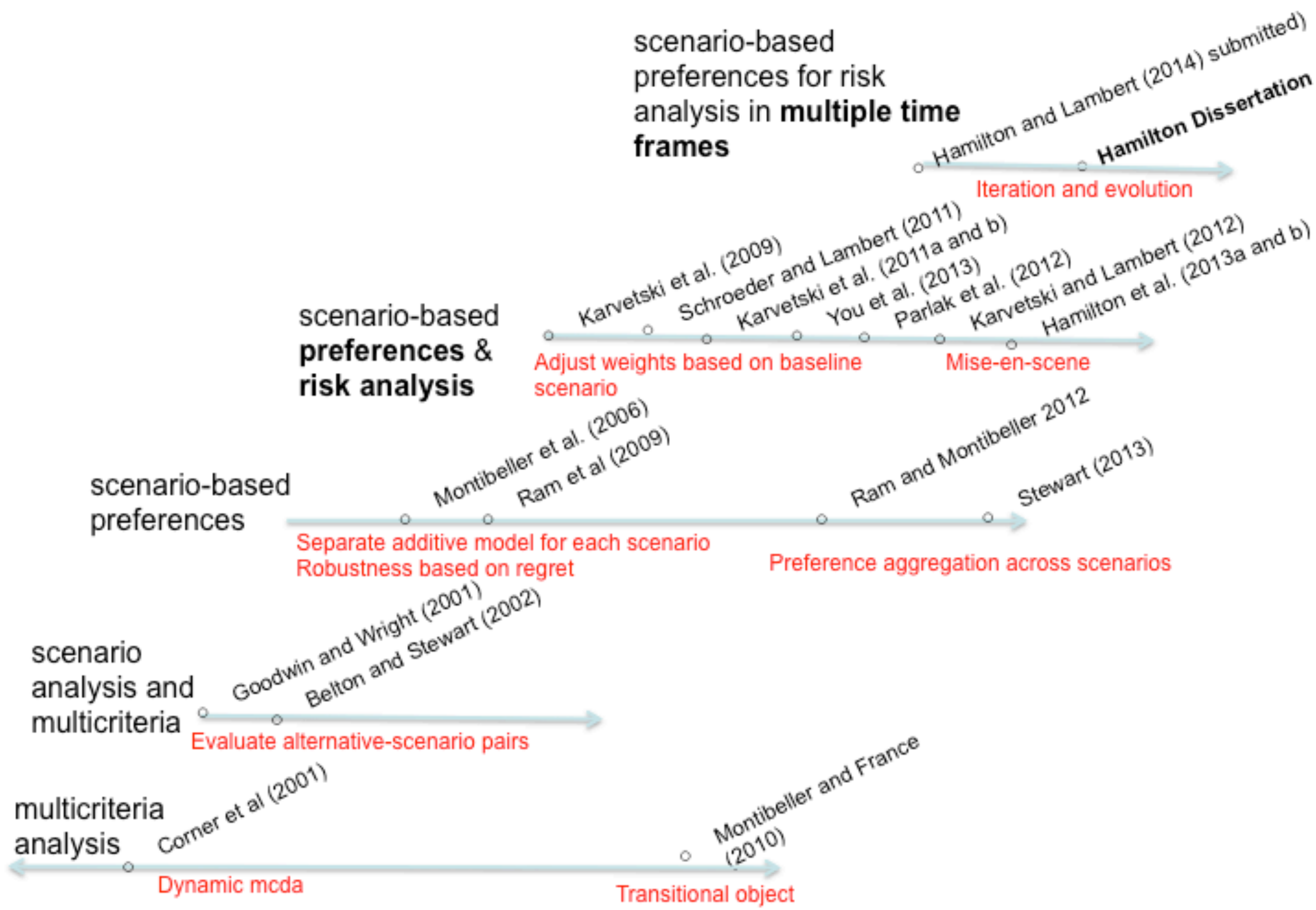

Figure 0-2: Contribution of dissertation to scenario-based preferences for risk analysis, in context of literature

7.4 Future Work

This section described several opportunities for future work. The most important is recommendations for the implantation of the philosophy in practical situations with many stakeholders. This includes the role of the facilitator/analyst and the level of coaching on multicritiria analysis and scenario analysis that is needed before or during the first meeting. Future research might include integration of other methodologies supporting risk identification, filtering and ranking (Haimes, et al., 2002) to generate scenarios. Another area of research might include integration of the repeated engagement with methods such as the Delphi method. The Delphi method is a widely used and accepted group communication process to gathering data from respondents within their domain of expertise and achieve consensus (Hsu and Sandford, 2007). The technique has been used to develop a full range of alternatives, explore or expose underlying assumptions, as well as correlate judgments on a topic spanning a wide range of disciplines (Hsu and Sandford, 2007).

Future research could extend the general philosophy to other multicriteria approaches other than multiattribute value theory described in Chapter 3. Another area for future research involves validation of the model process effectiveness. A potential survey was described in Chapter 6, which could be developed further.

7.5 Conclusion

This dissertation has extended the theory of scenario-based preferences for risk analysis across multiple time frames. The theory of scenario-based preference analysis is built on the recognition that risk scenarios during strategic design of complex systems is not equivalent to events in a probability space (Karvetski, 2012, 2011d). This dissertation further asserts that strategic problems have evolving initiatives, criteria, and uncertainties and thus, the risk analysis should be repeated over time as stakeholders gain insight over time. Each frame of scenario-based preference analysis contributes to the ability of stakeholders to identify a more comprehensive set of risk scenarios and a more refined set of initiatives and criteria.

This dissertation represents the theory, methodology, an application of research that has been disseminated in literature (Hamilton et al. 2013a; 2013b; 2014a, Hamilton and Lambert 2014 (submitted to *Reliability Engineering and System Safety*) and Hamilton et al. 2014b (submitted to ASCE-ASME Journal of Risk and Uncertainty) and in several conference proceedings (Hamilton and Lambert 2013; Hamilton and Lambert 2012; Hamilton and Lambert 2011; Hamilton et al. 2010, Lambert et al. 2011a; 2011b; 2011c; 2011d; 2010).

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Appendix A : Supporting Software

An excel workbook was designed to support the evaluation of scenario-based preference analysis. The workbook allows users to input initiatives, criteria, evaluate the criteria against each objective and weight the criteria. It allows users to define several scenarios and specify the adjusted weight of each scenario on the criteria. The software calculates and displays the value scores and ranking for each initiative under each scenario. The workbook also calculates the metric sum of square ranking changes for each scenario **Error! Reference source not found.** through Figure A-4 show screen shots from the software tool. A website is also available to download the workbooks for the second case study at http://www.virginia.edu/crmes/USACE_climatechange/. A screen shot of this website is displayed in Figure A-5.

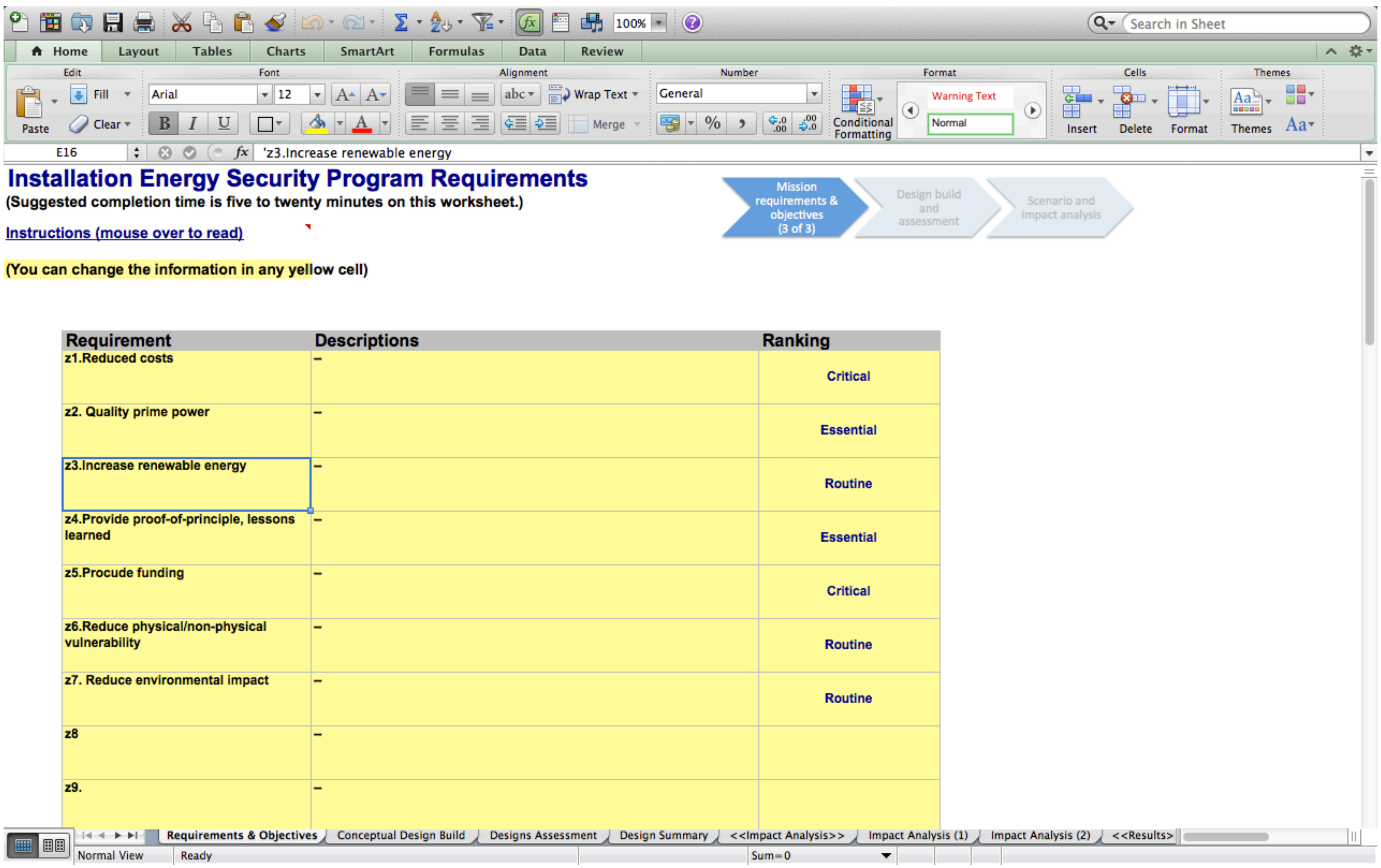

Figure A-1: Example of preference elicitation for criteria coefficients for energy security investments software tool.

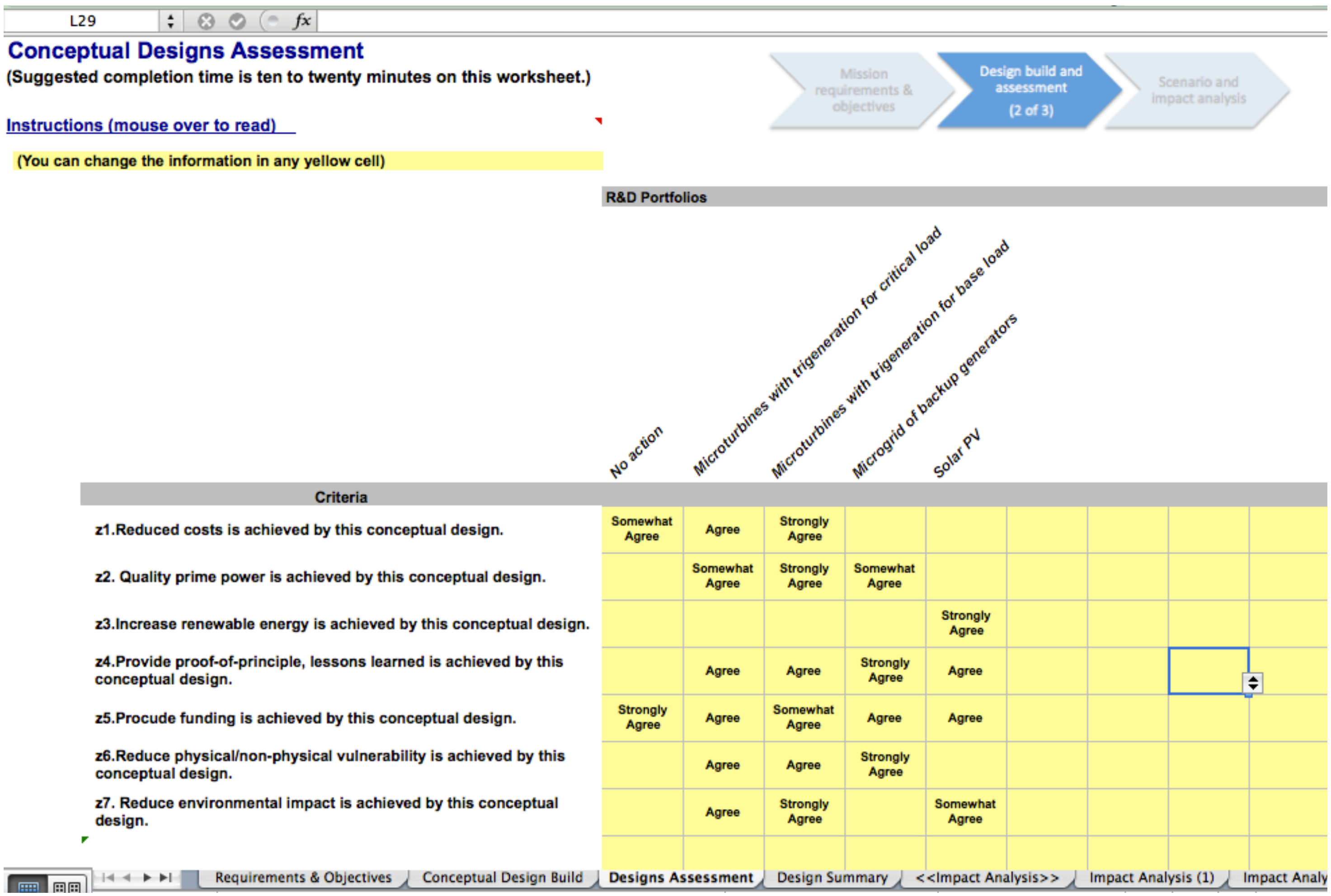

Figure A-2: Example of evaluation of initiatives on criteria in software tool.

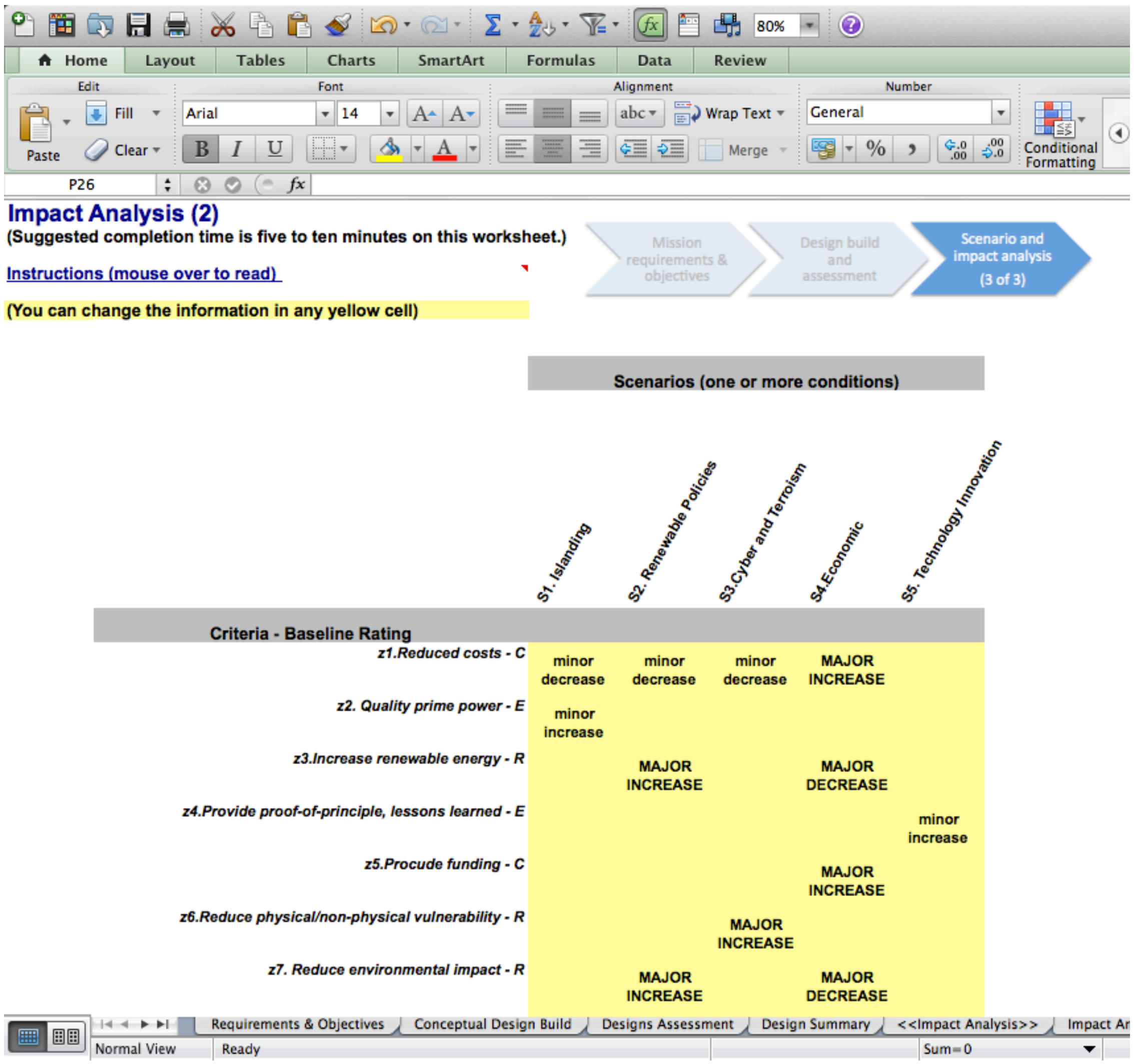

Figure A-3: Example of updating scenario-based preference adjustments in software tool.

K99 fx =K86

Conceptual Design Scores

Below are the scores (out of 100, with 100 being the best) that each conceptual design received under the baseline and each scenario.

	a1 Backup generators	a2 Microturbine trigen electrical critical load	a3 Microturbines trigen electrical critical load, thermal -	a4 Microturbines trigen electrical base load	a5 Microturbines trigen thermal base load, backup gen,	a6 High solar and high battery storage
Baseline	37	33	37	56	70	48
S1. Service charge	70	33	35	42	69	23
S2. Time of Day	31	7	29	15	43	92
S3. Demand Response	71	7	9	15	43	92
S4. Renewable Value Streams	12	7	9	15	43	92
	37	33	37	56	70	48
Median Score	37	20	32	29	56	70

The diamond under each conceptual design represents the baseline score the design received.
The bar extension from the diamond represents the range of scores that the conceptual design received.

Figure A-4: Example of output imbedded in software tool: value scores for each initiatives

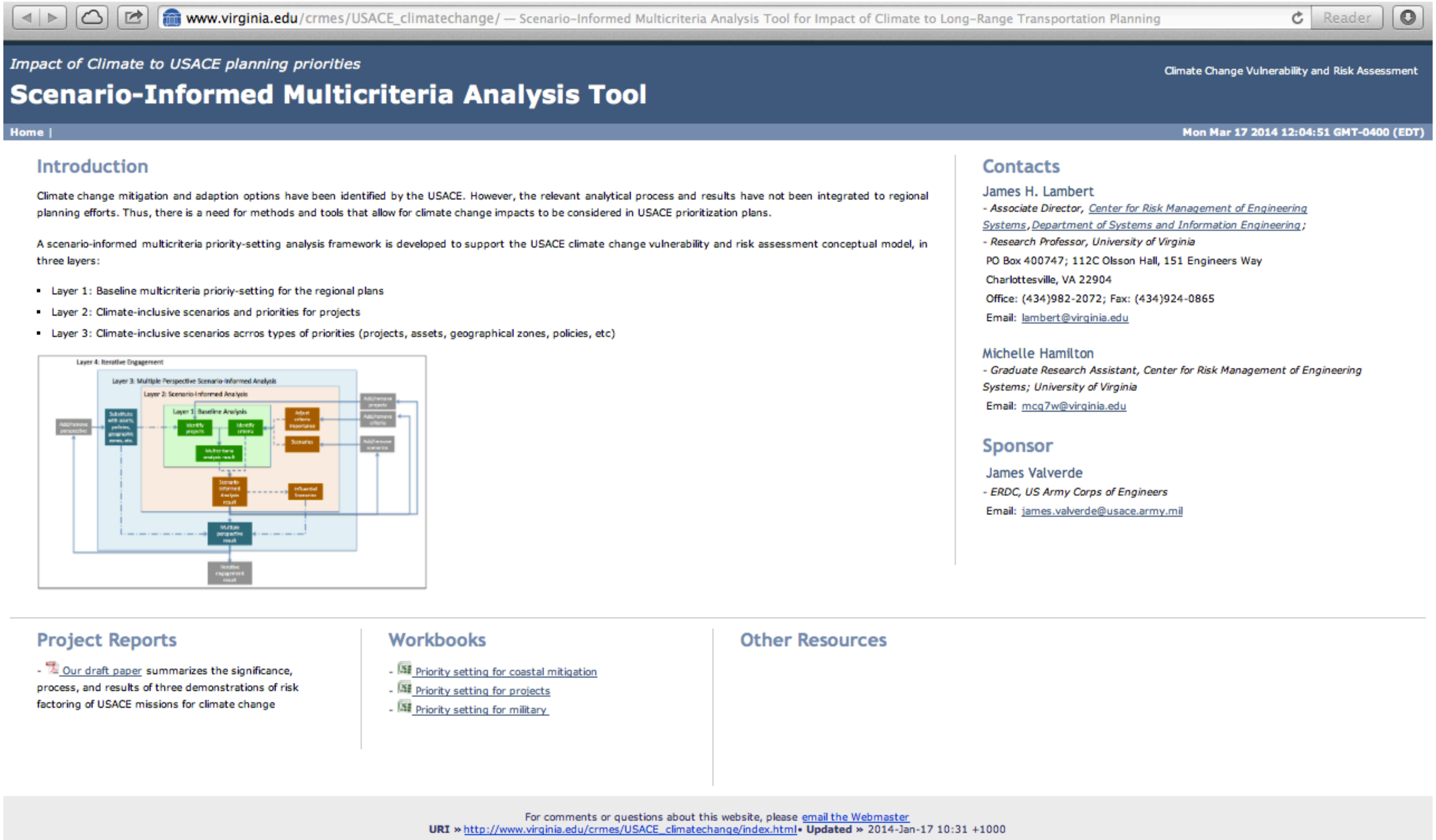

Figure A-5: Website resource to download software tool to support scenario-based preference analysis for risk

Appendix B : Supporting Information for Energy Security for Installations Case Study

This Appendix includes tables from Karvetski and Lambert, 2012 to provide supporting information for the first frame – *conceptual design priorities for an installations.*

Table B-1: Objectives, criteria, and value functions for first frame (from Karvetski and Lambert 2012)

Objective	Criterion	Value function
Reduced costs	Z^1 = twenty-year net present lifecycle value beyond no action alternative, in $ millions, $Z^1 = [z^{1o}, z^{1*}] = [0, 8.6]$	$v_7(z_i^7) = z_i^7/8.6$
Quality, prime power for five buildings	Z^2 = number of yearly hours of outages that would have been given expected outages of past years, $Z^2 = [z^{2o}, z^{2*}] = [0, 55]$	$v_7(z_i^7) = z_i^7/55$
Achieve Governmental Goals (AESIS; US Army 2009)	Z^3 = Number of AESIS goals achieved: 1. Reduced energy consumption 2. Increased energy efficiency 3. Increased renewable/alternative energy 4. Assured access to sufficient energy	$v_7(z_i^7) = z_i^7/3$, as at most three are achieved by any alternative
Provide proof-of-principles, lessons learned	$Z^4 = \begin{cases} 1, \text{if new technology is applied in an innovative way} \\ \frac{2}{3}, \text{if new technologies are used} \\ \frac{1}{3}, \text{if existing technologies are used} \\ 0, \text{otherwise} \end{cases}$	$V_4(z_i^4) = z_i^4$
Procure funding	Z^5 = expected time to wait until procure funding in years, $Z^5 = [z^{5o}, z^{5*}] = [0, 1]$	$V_5(z_i^5) = z_i^5$
Reduce physical/non-physical vulnerability	$Z^6 = \begin{cases} 1, \text{if removes most points of vulnerability} \\ \frac{2}{3}, \text{if removes some points of vulnerability} \\ \frac{1}{3}, \text{if removes a point of vulnerability} \\ 0, \text{otherwise} \end{cases}$	$V_6(z_i^6) = z_i^6$
Reduce environmental impact	Z^7 = CO_2 emissions reduced when compared to the no-action alternative in tons per year, $Z^7 = [z^{7o}, z^{7*}] = [0, 6500]$	$v_7(z_i^7) = z_i^7/6500$

Table B-2: Criteria coefficients for the baseline scenario (from Karvetski and Lambert 2012).

λ_1 Reduced costs	0.12
λ_2 Quality, prime power	0.27
λ_3 Achieve AES goals	0.12
λ_4 Provide proof-of-principle	0.27
λ_5 Procure funding	0.12
λ_6 Reduce physical/non-physical vulnerability	0.05
λ_7 Reduce environmental impact	0.05

Table B-3: Value scores for each initiative across criteria (from Karvetski and Lambert, 2012)

	a_1 (no-action)	a_2 (bury lines)	a_3 (microturbine-A)	a_4 (microturbine-B)	a_5 (backup generators)	a_6 (reconfiguration of lines, switches, breaks)	a_7 (microgrid)
Reduced costs	0.00	0.00	1.00	0.67	0.00	0.67	0.67
Quality, prime power	0.00	0.33	1.00	1.00	0.67	0.67	0.67
Achieve AES goals	0.00	0.33	1.00	1.00	0.33	0.33	1.00
Provide proof-of-principle	0.00	0.00	0.67	1.00	0.33	0.00	1.00
Procure funding	0.00	0.67	0.67	0.33	1.00	0.67	0.33
Reduce physical/non-physical vulnerability	0.00	0.33	0.67	0.67	0.33	0.33	1.00
Reduce environmental impact	0.00	0.00	1.00	1.00	0.00	0.00	0.67

Table B-4: Normalized adjusted criteria coefficient values for each of the five scenarios (from Karvetski and Lambert, 2012)

	s_1 Cyber	s_2 Natural disaster	s_3 Human error, disgruntled	s_4 Terrorist	s_5 International economic fear
λ_1 Reduced costs	0.4	0.4	0.4	0.4	0.3
λ_2 Quality, prime power	0.23	0.32	0.21	0.32	0.17
λ_3 Achieve AES goals	0.11	0.17	0.21	0.17	0.10
λ_4 Provide proof-of-principle	0.23	0.17	0.21	0.17	0.17
λ_5 Procure funding	0.11	0.09	0.09	0.09	0.17
λ_6 Reduce physical/non-physical vulnerability	0.23	0.17	0.21	0.17	0.06
λ_7 Reduce environmental impact	0.04	0.04	0.04	0.04	0.03

Appendix C : Stakeholder Process Evaluation

This appendix contains an example of a stakeholder evaluation of the process and output effectiveness (see section 6.2) of the scenario-based preference method described in this dissertation. This survey was completed by an employee of the U.S. Army Corps of Engineers in regards to the second case study – climate change and coastal infrastructure.

Valverde, J.

Stakeholder Survey

Date: 1/27/2014 **Organization: USACE ERDC**

Process Evaluation

1. Extent of participation by people in your organization in the problem solving process

(a) **Iterative Scenario-based MCDA**: How participatory do you rate the decision analysis process? (Please indicate your answer by writing a "DA" at the appropriate point on the scale below.)

(b) **Ideal**: How participatory should similar problems ideally be solved in your organization? (Please mark this ideal state with an "I" at the appropriate point on the scale below.)

(c) **Status Quo**: How participatory would the decision problem at hand or similar problems have been solved with the existing processes/methods (Please mark this with "SQ" at the appropriate point on the scale below.)

Not very participatory, including few opinions within the organization	1	2	3	4	5	6	7	Very participatory, including a variety of opinions within the organization

2. Extent of top-down versus bottom-up influence in your organization during problem-solving processes

(a) **Iterative Scenario-based MCDA**: How do you rate the decision analysis process in terms of bottom-up versus top-down influence? ("DA")

(b) **Ideal**: How should similar problems ideally be solved in your organization in terms of bottom-up versus top-down influence? ("I")

(c) **Status Quo**: With how much bottom-up/top-down influence would the decision problem at hand or similar problems have been solved with the existing processes/methods? ("SQ")

Strongly top-down driven (mainly decided by top-level management)	1	2	3	4	5	6	7	Strongly "bottom-up" (including middle management influenced)

3. Extent of transparency and comprehensibility not mutually exclusive

(a) **Iterative Scenario-based MCDA**: How do you rate the transparency and comprehensibility of the decision analysis process? ("DA")

(b) **Ideal:** With how much transparency and comprehensibility should similar problems ideally be managed in your organization? ("I")

(c) **Status Quo**: How transparently and comprehensibly would the decision problem at hand or similar problems be solved with the existing processes/methods? ("SQ")

Complex, not very transparent and comprehensible	1	2	3	4	5	6	7	Highly transparent and comprehensible

4. Contribution of rational analysis and intuitive judgment

(a) **Iterative Scenario-based MCDA**: How do you rate the decision analysis process in terms of rational analysis versus intuitive judgment? ("DA")

(b) **Ideal**: How should similar problems ideally be solved in your organization in terms of rational analysis versus intuitive judgment? ("I")

(c) **Status Quo**: How rationally analyzed versus intuitively judged would the decision problem at hand or similar problems be solved with the existing processes/methods? ("SQ")

Mostly based on intuitive decision making	1	2	3	4	5	6	7	Mostly based on rational analysis

5. Extent to which creativity or traditional ideas contribute to problem-solving

(a) **Iterative Scenario-based MCDA**: How do you rate the decision analysis process in terms of simulating creativity? ("DA")

(b) **Ideal**: How should similar problems ideally be solved in your organization in terms of creativity-stimulation versus based on established ideas? ("I")

(c) **Status Quo**: How creatively versus "established" would the decision problem at hand or similar problems be solved with the existing processes/methods? ("SQ")

Less creativity-simulating, more based on "established" ideas	1	2	3	4	5	6	7	Highly creativity stimulating, less based on "established" ideas

6. Extent of interactivity and dialogue-orientation ("Quality" of information flow)

(a) **Iterative Scenario-based MCDA**: How interactive and dialogue-oriented do you rate the decision analysis process? ("DA")

(b) **Ideal**: How interactively and dialogue-oriented should similar problems ideally be solved in your organization? ("I")

(c) **Status Quo**: How interactively and dialogue-oriented would the decision problem at hand or similar problems be solved with the existing processes/methods? ("SQ")

Less interactive and less dialogue-oriented	1	2	3	4	5	6	7	Interactive and dialogue-oriented

7. Extent of information exchange (Quantity of information flow between different stakeholders)

(a) **Iterative Scenario-based MCDA**: How do you rate the decision analysis in terms of facilitating information exchange between different stakeholders? ("DA")

(b) **Ideal**: Ideally, how much information exchange between different stakeholders should occur when similar problems? ("I")

(c) **Status Quo**: How much information exchange would occur in the decision making process with the existing processes/methods for the problem at hand or similar problems? ("SQ")

Little exchange of information	1	2	3	4	5	6	7	Extensive exchange of information

8. Extent of strategic insights

(a) **Iterative Scenario-based MCDA**: How do you rate decision analysis process in terms of creating strategic insights which can be used for follow-up or different projects? ("DM")

(b) **Ideal**: To what extent should decision processes for similar problems create strategic insights rather than strictly problem-related results? ("I")

(c) **Status Quo:** To what extent would existing processes/methods create strategic insights for the problem at hand or similar problems? ("SQ")

Somewhat less strategic insight	1	2	3	4	5	6	7	More strategic insights

9. Challenge to strategic priorities

(a) **Iterative Scenario-based MCDA**: How do you rate the decision analysis process in terms of the extent to which strategic priorities are challenged? ("DM")

(b) **Ideal**: To what extent should decision processes for similar problems ideally challenge strategic priorities for the decision problem at hand or similar problems be solved with? ("I")

(c) **Status** Quo: To what extent would existing processes/methods challenge strategic priorities for the decision problem at hand or similar problems be solved with? ("SQ")

Strategic priorities not challenged, focus on an optimal solution	1	2	3	4	5	6	7	Strategic priorities challenged, focus on a robust solution

Output Evaluation

There are several outputs that it would be useful to evaluate. The objective

1. How do you rate the decision analysis process in terms of identifying new criteria not previously identified? ("DM")

No new criteria were identified	1	2	3	4	5	6	7	New scenarios were identified

2. Extent of initiative identification
How do you rate the decision analysis process in terms of identifying new initiatives not previously identified? ("DM")

No new initiatives were identified	1	2	3	4	5	6	7	New initiatives were identified

2. Extent of scenario identification
How do you rate the decision analysis process in terms of identifying new scenarios not previously identified? ("DM")

No new scenarios were identified	1	2	3	4	5	6	7	New scenarios were identified

Appendix D : Timeline of Contributions and Dissemination of Research

Table D-1: Relevant experience and dissemination of this dissertation throughout paper, conference, presentation, and workshops

	JUNE 2010	DEC 2010	JUNE 2011	DEC 2011	JUNE 2012	DEC 2012	JUNE 2013	DEC 2013	Jan 2014
Energy Rodeo, Fort Bliss, TX	+								
Fort Belvoir energy working group	+	+	+	+					
Energy system development for military installation project	+	+	+	+					
Presentation at SRA annual meeting, Salt Lake City		+							
Defended master's thesis		+							
Presentation at USACE Infrastructure Systems Conference, Atlanta, GA.			+						
Presentation at IEEE ITMC Conference, San Jose, CA			+						
Honorable Mention, 2011 SAME Sustainability Award for education and outreach			+						

	JUNE 2010	DEC 2010	JUNE 2011	DEC 2011	JUNE 2012	DEC 2012	JUNE 2013	DEC 2013	Jan 2014
Hamilton gave presentation at SRA annual meeting, Charleston, S.C.				+					
Archival paper Hamilton et al., 2013 in *ASCE Journal of Infrastructure Systems*						+			
Archival paper Hamilton et al., 2013 in *Environmental Systems and Decisions.*						+			
Presentation at SRA annual meeting, San Francisco, CA.						+			
Book Chapter accepted, Hamilton et al., 2013						+			
NAE National Institute for Energy Ethics and Society workshop in Tempe, AZ							+		
Adaptive disaster response risk-based decision aiding software for USACE TEC								+	
Presentation at SRA annual meeting, Baltimore, MD								+	
Archival paper submitted, Hamilton and Lambert. 2013 to *Risk*, *Reliability and System Safety*								+	
Archival paper submitted, Hamilton, Lambert, and Valverde. 2013 to *ASCE-ASME Journal of Risk and Uncertainty*									+