LMI Sponsored Research

A Multiobjective Benefit-Cost Framework for the Analyses of Net Zero Water Alternatives

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Summer 2011

GW EEM Environmental & Energy Management

Environmental and Energy Management Program

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC

Department of Engineering Management and Systems Engineering

School of Engineering and Applied Science

Research Project: LMI/GW/EMSE-SU11-2

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ACKNOWLEDGEMENT

Funding for this study was provided by the Logistics Management Institute (LMI) through the Engineering Management and Systems Engineering Department (EMSE) of the School of Engineering and Applied Sciences, The George Washington University. I wish to acknowledge the guidance and intellectual support generously provided by my Academic Advisor, Dr. Jonathan P. Deason, Dr. Francis Reilly from the Logistics Management Institute, Dr. Rene Van Dorp, Dr. Julie Ryan, Dr. Michael R. Duffey, and other members of the peer review team composed of selected EMSE faculty.

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Abbreviations

AHP	Analytical Hierarchy Process
DoD	Department of Defense
DoE	Department of Energy
GIGS	Group Ideas Generation and Structuring
ISM	Interpretive Structural Modeling
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
NGT	Nominal Group Technique
NZW	Net Zero Water
SME	Subject Matter Experts
OCONUS	Outside the contiguous United States
PROMETHEE	Preference Ranking Organisation METHod for Enrichment Evaluations
SAW	Simple Additive Weighting
SMART	Simple Multi-Attribute Rated Technique

1. Introduction

National security obviously is a complex issue. Successful performance of the defense mission requires consideration of multiple objectives and challenges, and depends on the availability of key resources. Like energy, water is a critically important resource for the successful conduct of Army operations, which in turn is vital to the success of our Nation's core defense mission. A stable and reliable supply of water resources must be secured to ensure mission achievement.

Despite this complexity, Section 2 (c) of Executive Order 13423 (2007) requires all Federal agencies to reduce life-cycle water consumption in a cost-effective manner by 16 per cent by the end of 2015, or by two per cent annually, using the 2008 fiscal year as a baseline.[i] Although this clearly is a daunting challenge, Army's Zero Water initiative, if undertaken properly, provides an excellent opportunity to meet the requirements of EO 13423 while addressing the complexities inherent in achieving "net zero water" in the context of national security.

1.1 Water Security and the Defense Mission

As defined by Dr. Marc Kodack of the Office of the Deputy Assistant Secretary of the Army for Energy and Sustainability, water security is "[t]he capacity to ensure that water of suitable quality is provided at a sustained rate sufficient to support all current and future Army missions as needed."[ii] In a strict defense context, proper water planning and management should not be viewed as objectives, but rather as tools to achieving the objective of national security by enabling defense operations and minimizing contributions of climate change to global instability.

Over time, perceptions of the value of water -- like energy and other mission essential resources -- have gradually evolved from that of "commodities" to "capabilities."[iii] In the defense context, water sustainability should not be viewed as a value in itself, but rather in the context of its contribution to national security in the broadest sense. For example, as articulated in the 2010 Quadrennial Defense Review, water conservation should not be achieved at the expense of the defense mission or other defense capabilities.[iv] DoD Strategic Sustainability Performance Plan also defines sustainability as "a means of improving mission accomplishment."[v] In the energy area, this same as articulated by the National Renewable Energy Laboratory when it stated that "[m]ission accomplishment is the top priority for installations."[vi]

Water security is a complex and multi-disciplinary issue. It involves environmental, technical, social, economic, and national security components.[vii] Each component calls for its own objectives, which at times become conflicting -- the best technical solution or the most secure one may be not the cheapest or the most socially acceptable. And vice versa -- addressing the interests of all stakeholders/social groups may lead to serious increase in risks to national security.

Water resources are used by defense forces in many different ways, such as field vs. installation water use, drinking vs. operational, direct vs. embedded and national vs. international.[viii] While all of these uses are important, differing degrees of flexibility exist regarding how best to meet specific needs. For example, when dealing with embedded water use, examination of procurement protocols and contractor procedures may yield opportunities to reduce total embedded water use beyond direct usage reductions. When dealing with direct water operational water use at the installation level, the analysis of both water treatment facilities and general water use practices is appropriate; either or both can be modified to curtail direct water consumption. On the other hand, options for water use reductions in tactical operations are much more limited.

1.2. Scale Considerations in Water Security

It is clear that the challenges of water security are highly location-specific. At the macroscale, national challenges differ substantially from global challenges. Water security in the national context involves consideration of challenges such as vulnerability to terroristic attack, resilience to natural and man-made disasters, protection of dams and water treatment plants, water rights allocation and seniority, and state law vs. Federal law. On the other hand, water security in the global context may more heavily emphasize considerations of challenges related to water quality control and purification, relationships between water and sanitation levels and political stability (or lack thereof) in theater operations, assurance of reliable water supplies for operations in hostile environments, and the fragility of foreign governments coping with global climate change.[ix]

A great degree of endogeneity exists among the lack of water resources in some overseas regions, the fragility of these states, likelihood of political and armed conflicts, and threat to U.S. defense missions.[x] As a result, it can be a challenging task to provide a guaranteed and secure water supply for the installations where success is most critical from the defense point of view. Domestically, the General Accounting Office, in its 2003 report to Congress on strategic planning considerations related to military facilities, emphasized the need for repairs and replacement of outdated water and sewage systems in military installations.[xi] Other important domestic challenges are water rights, interactions with local communities, and federalism considerations.

Several blue ribbon reports in recent years have expressed concern about the effect of global environmental changes, including water quantity and quality concerns, on national security, characterizing them as "threat multiplier[s] for instability in some of the most volatile regions of the world."[xii] The effects of environmental degradation can be felt worldwide, and include ozone depletion, acid rain, reduced biodiversity, overall resource depletion with simultaneous human population growth, and greenhouse effect.[xiii] Limited resources almost always lead to conflicts. As environmental conditions worldwide deteriorate and people have less access to key natural resources, political changes in some African, Asian, and Middle Eastern countries may favor extremist and radical movements, potentially leading to increased terrorism threats. Other consequences of global environmental degradation likely will include increased immigration from unstable states to Western European countries, an increased need international and American humanitarian organizational; services, and an increased demand for the involvement of international peacemakers.[xiv] By reducing its environmental "bootprint," including reduced water and energy consumption, the U.S. defense sector can reduce these effects, leading to decreased vulnerability and improved preparation for future challenges.

At the microscale, local water supplies – in terms of both quantity and quality - vary substantially from installation to installation. Military installations face quite dissimilar operating environments due to differing geographical locations, climatic and socio-political conditions, and operational missions. In addition, water delivery challenges in tactical operations typically differ substantially from those of non-tactical situations. Beyond these fundamental considerations, relationships with local communities -- both domestically and outside the contiguous United States (OCONUS) -- may be very different. For example, sometimes installation objectives are in conflict with surrounding community objectives, such as when providing assured supplies for the defense mission reduces water availability for the local populace.

1.3. The Net Zero Concept

While the net zero concept originated in the domain of energy, it was only a matter of time for this concept to be applied to water as well. However, the initial "energy definition" of net zero (zero net direct and embedded consumption using a life-cycle approach) cannot be applied directly to water. A principal reason why this is true is that most currently used energy is produced (from fossil or nuclear fuels) rather than captured (some types of renewable energy), while most water is captured and redistributed (water treatment and supply) rather than produced. Therefore, a much greater degree of flexibility for energy exists in terms of where to place the source (generator) than is the case for water. While solar panels can be installed on demand almost anywhere, we cannot as easily move water sources to desired use locations.

Another reason concerns the greater variety of available energy sources (oil, gas, water, nuclear, biomass, solar, geothermal, and so on) as compared to water sources. With energy, many options (solar, wind, geothermal, etc.) exist from which to find the most available, appropriate and cost-efficient source for specific locations, whereas for water, options are limited to using local surface or ground water sources, or transporting water.

A third reason is that, with current technologies, it is possible to produce all needed energy on a given installation -- making the installation independent of the external energy sources. At the current level of water supply technology, it is not possible to make most installations truly independent from external water supplies.

Finally, when dealing with the water, we are concerned both with the quantity and quality of water taken from the natural ecosystem and returned to it. Zero net water consumption using a life cycle approach means, among other things, that wastewater is treated appropriately before being returned to the watershed and that discharges of water-treatment chemicals are minimized. In this way, quantities of wastes and chemicals introduced into ecosystems can be minimized so that natural assimilative capacities of the environment are not exceeded.[xv]

2. Net Zero Water in Defense Installations: Need for a Multiobjective Approach

In the spring of 2011, the U.S. Army identified 18 pilot net zero projects, six in each of the categories of water, energy and waste. Two additional installations volunteered to attempt to achieve integrated net zero in energy, water and waste: Fort Bliss, Texas, and Fort Carson, Colorado.

The following were selected as Net Zero Water pilot installations:

1. Aberdeen Proving Ground, Maryland
2. Camp Riley, Oregon
3. Fort Buchanan, Puerto Rico
4. Fort Riley, Kansas
5. Joint Base Lewis-McChord, Washington
6. Tobyhanna Army Depot, Pennsylvania

In these locations consumption of fresh water were to be minimized, with all return flows to occur in the same watersheds as the diversions.[xvi]

2.1. Evolution of the Net Zero Water Definition in a Defense Context

An early definition of net zero water consisted of a single objective: to minimize net consumptive use. A non-defense net zero water development generally is defined as that which achieves net zero water consumption by minimizing net consumptive use, returning freshwater to the same watershed, and preserving both the quantity and the quality of both ground and surface water in the region. This also became an initial definition for the Army Net Zero Water Installation.[xvii] In contrast to that single objective approach, the Department of Defense Strategic Sustainability Performance Plan, prepared in 2010, includes the following water-related goals: reduce water consumption intensity for both potable and irrigation/industrial purposes, preserve the pre-development hydrology for all development and redevelopment projects with area of 5,000 square feet or more, reduce "the environmental and mission risks associated with chemicals," and improve accountability regarding the amount and application of chemicals that pose environmental concern.[xviii]

Relevant literature is replete with references to other objectives appropriate for evaluating alternatives related to net zero water in the Army. Examples include maximization of installation security and resilience (islanding), and minimization of cost, cost volatility, environmental impacts, and interference with operations of other agencies.[xix] While such objectives typically are identified for energy, many apply equally well to water. And like energy, as resources dwindle, competition grows stronger and the uncertainty of future supplies increases.[xx] As set forth in many defense documents, long-term strategic planning is critically important to achieve the best defense results, create conditions for true sustainability of defense operations, and reduce uncertainties in the future.[xxi,xxii]

2.2. Evolution of Multiobjective Analytical Tools

To help decision makers deal with complex analytical problems such as the net zero water challenges described above, many approaches to multi-criteria decision analysis (MCDA) were developed in second half of 20th century. These methods directly address the incommensurability of objectives and criteria commonly associated with complex problems. Some methods facilitate the acquisition of knowledge and information that is accumulated and stored in the minds of subject matter experts (SMEs) but not readily available otherwise. Typical MCDA methods help to "structure the problem," refine the formulation of alternatives during the analytical process, incorporate subjective preference rankings of SMEs, and assist decision makers to arrive at decisive results/conclusions about which alternative to select.[xxiii, xxiv] Such methods can help to achieve more robust, structured, defendable results, and minimize the risk associated with strategic decision-making.[xxv]

Using a multi-criteria approach allows making informed and balanced decisions about "specific actions, time frames, responsibilities, and funding" that are needed for defense installations to perform their missions.[xxvi] The multi-criteria approach is particularly well suited to the challenge of optimizing contributions of portfolios of net zero water alternatives to the evolving multiple objective orientation of net zero water as reflected in the statement made by the Office of the Assistant Secretary of the Army (Installations, Energy & Environment) that "We are creating a culture that recognizes the value of sustainability measured not just in terms of financial benefits, but benefits to maintaining mission capability, quality of life, relationships with local communities, and the preservation of options for the Army's future."[xxvii]

3. Research Approach

The objective of the research summarized in this document was to design a multi-criteria decision aiding methodology to assist Net Zero Water pilot installations in evaluating alternatives to achieve net zero water. Attainment of this objective requires that we (1) clarify the definition of net zero water in defense sector, (2) set forth clear objectives, (3) identify criteria for measuring the performance of alternatives towards objectives, (4) develop metrics to measure contributions of alternatives towards objective, and (5) develop a transparent tool to calculate costs and benefits of Net Zero Water in a defense setting.

Illustrations of objectives, criteria and metrics relevant to the investigation of the net zero water challenge in the context of US defense installations are provided in the table below:

Examples of objectives:	Minimize cost	Minimize environmental impacts	Maximize contributions to mission capability
Examples of criteria:	Cost	Environmental parameters such as chemical discharges	Reduction of vulnerabilities to terrorist attack and other measures of installation independence
Examples of metrics:	Cost reduction measures	Measures of chemical/disinfectant use	Volumetric dependence on external water sources (related to water consumption reductions)

Properly constructed, a multi-criteria decision aiding tool can be highly effective in developing solid benefit-cost data to (1) support alternatives analyses and improve decision-making, and (2) demonstrate the validity of Department of the Army recommendations to DOD, OMB and the Congress.

4. Development of a Multi-Criteria Tool to Support Net Zero Water Analyses in a Defense Context

4.1. Considerations in Tool Design

Resources can have multiple uses, and this holds true for water as well -- water can be used to achieve various economic, social, political and environmental goals.[xxviii] When resources are limited, goals can become conflicting. One type of use may deplete the quality or quantity of an available water resource, making it unavailable for other types of uses. [xxix] In such cases, resource management requires conflict analysis and ranking of multiple goals according to priorities in order to achieve the greatest utility from the limited resource.[xxx]

However, the achievement of optimal water management for defense installations requires a somewhat different and more complex approach. We are not as much concerned with selecting among possible alternative consumptive uses of a limited resource (water). Instead, we are dealing with multiple goals and multiple but limited resources, water being one of them, to achieve these goals. Challenges associated with such strategic decision-making include "high levels of uncertainty and decision complexity."[xxxi] From the perspective of a decision-maker, the sources of uncertainty/risk include "unquantifiable information, incomplete information, non-obtainable information, (and) partial ignorance."[xxxii] The uncertainty factor is especially critical for water resource availability in some foreign locations.

Strategic water management decisions are intricate because they must address security, economic, "social, psychological, physico-chemical and geological aspects."[xxxiii] In most cases, complete and exhaustive information is not available for all of these factors, their combinations (real time or inter-temporal), constraints and tradeoffs among goals. Sometimes it is impossible to collect "precise, certain, exhaustive and unequivocal" information about all system components, or collecting information would require too much time and will be prohibitively costly.[xxxiv] In a general definition suggested by Zimmermann and modified by Stewart: "Uncertainty implies that in a certain situation a person does not possess the information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behavior or other characteristics."[xxxv, xxxvi] It is not possible to fully eliminate the uncertainty in the case of water management and security decisions; however, we can minimize the risk of arriving at undesirable outcomes.

Other practical challenges are caused by the fact that water management decisions require a commitment of large amounts of financial resources, have very long-term implications, and can influence all other systems within organizations and installations. Decisions made today also can restrict future alternatives for organizations, which can serve as disincentives for making decisions. For example, if an organization demonstrates that it can greatly reduce water consumption, it can be bound to the lower consumption level by new, top-down plans and budgets. And, since defense facilities presently do not benefit from savings directly, they face the risk of incurring resource deficits if in the future they cannot save at the same level. Such problems of split incentives are discussed quite extensively in recent documents on energy and water efficiency in defense facilities.[xxxvii]

Multi-criteria decision methods in such situations may "not … provide a unique criterion for choice; rather [help] to frame the problem of arriving at a political compromise," provide insight into the existing problem, or rank decision alternatives in order of their priority.[xxxviii, xxxix] To receive a more definitive guidance on which option will be most efficient in achieving organizational mission and goals, a decision maker can combine the MCDA with cost-benefit analysis.[xl]

4.2. Strategic Decision-Making and Multi-Criteria Decision Analysis

Decisions regarding water management and water security are strategic -- they are made by top officials, require commitment of significant resources, affect both organization and stakeholders outside of the organization, and cause results experienced for long periods of time. Because of the complexity of alternatives and different and unmatched criteria units, it is often challenging to compare available alternatives and select the best one.

As mentioned erlier, the research summarized herein was focused on several strategic and tactical tasks: clarify the goals, identify objectives, generate alternatives for achieving these goals, and develop criteria and metrics for decision-making. Decision-making relies on judgements about “flow of influences” organized into structures.[xli] Usually, in order to find out where we want to go and how can we get there, we first need to know where we are presently. This typically involves defining a clear picture of “objective reality.” The normal scientific approach to accomplish this task involves collecting data describing (the fragment of) objective reality; organizing and structuring it; analyzing and interpretingteh data; and developing a model that can reliably, consistently, and accurately explain the present and predict the future.[xlii] Some types of research questions also require collection of data over a period of time in order to be able to understand the variability inherent in “objective reality.”

As has been noted earlier in this report, the US defense program is very large --installations are located both nationally and internationally, operations vary widely in type and nature, and the terrain (social, environmental, economic and political) varies significantly as well. Because of this reality, direct collection of information for <u>all</u> installations for the purpose of processing and structuring it into a descriptive or predictive model is at the present time infeasible. Therefore, the approach recommended herein inlvovles selection of a representative sample of defense installations, understainding that dtata collection for some installations would be a significantly problematic, costly and time-consuming task.

Net Zero Water projects are decentralized in nature -- they present location-specific challenges and opportunities. Polatidis et al. (2006) developed the schematic representation of impacts from transition to renewable energy sources and features of decision-making in this context.[xliii] The scheme is presented in the Appendix (Figure 1), with our slight modifications to make it suitable for the case of NZW defense installation. There are multiple factors, including multiple goals and objectives. Some of them can be described quantitatively, and others only qualitatively, it is not always possible to compare them directly.

4.3. Data Collection

There are two aspects of method selection: the best method for collecting data and best method for processing and structuring data into a model to assist with decision making. The process used for method selection for both aspects in the research described herein is summarized in this section and in the next section.

A typical process for developing data relevant to objectives determination, criteria identification and metric specification involves interviewing people who have been observing/experiencing relevant processes through their professional activity. We refer to these people as subject matter experts (SMEs). By the nature of their work, SMEs often are decision makers in addition to being subject matter experts. SMEs also can become a source of data/information in decision-making research and analysis. Typically SMEs have first-hand experience working with topics of interest during the period of interested. While information stored in SME brains may be not too detailed, it may nonetheless be quite valuable. SMEs commonly have "collected" relevant information, processed and analyzed it, and stored the most essential points and possibly discarded some irrelevant "data entries."

In a way, SMEs have done part of researcher's job. An appropriate objectives hierarchy already exists in their minds, possibly in a fragmented form. Most likely their "model" is quite subjective and tightly focused. It is not a "complete picture," yet this knowledge is not public, and not readily available to other experts and decision-makers. Decision-makers and researcher do not know how the complete hierarchy looks, nor the identity of relevant components: goals, objectives, criteria and attributes. The task of the researcher is to collect the knowledge from SMEs and develop a hierarchy/model based on such knowledge. Several different techniques exist to elicit knowledge from SMEs, as discussed in greater detail later in this report.

4.4 Analytical Method Selection

Now, let us address identification of the best tools and techniques for structuring the data, and information elicited from the SMEs into an appropriate and useful decision aiding model. Multi-criteria decision analysis consists of a class of methods that can operationalize multiple incommensurable goals, objectives and criteria in a manner appropriate to our research problem. Next, we need to select a specific type of MCDA for our research. Every scholarly source reviewed in the is reserch stresses that there is no "one for all" best tool to solve a multiobjective problem. The choice of tool and research technique will be defined by (1) the type of information/knowledge available, (2) the manner in which such information can be collected, (3) local conditions andchallenges, (4) goals and alternatives, and (5) accessiblity and cooperativeness of the SMEs. If criteria are incomparable and incommensurable, one of outranking methods would be appropriate. If all criteria are directly comparable and commensurable, the utility-based methods can be applied.[xliv] A schematic illustration for MCDA method selection was developed by Pollatidis et al. (2006) and is provided in the Appendix (Figure 2). Selection of an appropriate MCDA method for the net zero water challenge is discussed in next sections of this report.

From a practical point of view, we would only be interested in a method that can establish a strong preference for one alternative rather than offering multiple (or infinite) alternatives. Also, the selected alternative should be feasible. Therefore the method should offer a single, descrete solution. We would also want to minimize the time burden of our research on SMEs, and choose a method that allows for flexibility in time and location of SMEs participation in research. If high rank, busy schedules, and dispersed geographical locations of experts dictate, it may be infeasible to organize group meetings and therefore procedures not requiring face-to-face meetings would be approroiate.

4.5. Role of Subject Matter Experts

As has been noted previously, the ability of a model to aid decision-maker depends on the quality and comprehensiveness of input information. Any predictive or descriptive model is a simplified and schematic portrayal of reality. On one hand, the more facets incorporated into the model, the better we will be able to describe reality and generate high quality advice for decision-makers. On the other hand, incorporating too many factors and variables could make the model too cumbersome and possibly computationally intractable.

Collection of too detailed and comprehensive information also can be infeasible due to the time requirements and the cost of such a process. Furthermore, sometimes the information available to date may be not fully adequate or relevant for making decision on completely new activities. In these cases, judgment of subject matter experts can be valuable. First, they may be able to collect and store, in some form, relatively comprehensive information about their field of expertise. Second, they not only store the information in its original form, but also analyze and transform it, establishing connections and links between different knowledge components. Finally, based on their knowledge of the subject matter, they can form judgments regarding new and future projects, even when no similar projects have been done previously – tackling the so-called "epistemic uncertainty".[xlv] These features of subject matter experts make their use for decision-making analysis extremely attractive.

An important element of collecting knowledge from SMEs is the process of their interactions with each other (knowledge and opinion exchange) while reaching consensus/compromise opinions. Therefore, not only should each individual SME be carefully selected, but also we must try to select a good group.[xlvi] We want to select SMEs representing different (to some extent) backgrounds to obtain comprehensive information on the research issue, yet we also want the SMEs to be able to understand each other and the context of the research. The task of the researcher is to design the knowledge collection *process* in a way that will allow the group of SMEs to reach consensus, and that will lead to the *result* of a single and robust preferred decision scenario.[xlvii]

There are two views on the process of formulating SMEs' knowledge into a structured for the purpose of MCDA: descriptive (positivist, Anglo-Saxon approach) and constructive (constructivist, "European" approach).[xlviii] The descriptive approach suggests that opinions of SMEs are fully crystallized, they have a firm view of priorities ranking and criteria importance, and they make decisions accordingly. Neither the researcher who collects opinions, nor the opinions expressed by other SMEs, can change the views of each particular individual on the topic of his/her expertise. Some researchers also differentiate normative and prescriptive approaches as subsets of the descriptive positivist approach.[xlix] The normative approach is used for models derived from norms that are necessary for rational behavior. The prescriptive approach deals with situations that arise when the decision maker possesses a complete set of knowledge necessary to make decisions but does not have an operational model to process this knowledge and generate decisions. The constructive approach assumes that each subject matter expert can adjust and modify their opinions in the process of study until the final version is fully formed and structured into the model.

Subject matter experts also can introduce the additional dimension of uncertainty into the decision-aiding process. The types of uncertainties described previously in this report were related mostly to the lack of knowledge about external factors and consequences of decisions, and usually are referred to as external uncertainties. The second class of uncertainties, internal, are inherent to the thinking process of decision-makers -- their “values and judgments”. [l]

5. Collecting Knowledge from Subject Matter Experts

5.1. Objectives Hierarchies

The objectives of the stakeholders, numerous aspects of the situation/issue, different ways to reach objectives, and multiple criteria to evaluate success or failure of each action – are all components of the decision-making problem. We assume that a decision results in *action*, and this action will have *consequences*. We also assume that there is a *preference system* that allows comparing actions, consequences, and decisions. If we were to make pairwise comparisons, there will be three possible results: preference (strong or weak) of one alternative in the pair, indifference between two alternatives, and incomparability.[li]

There is no complete consistency in the use of terms across MCDA literature, although all authors use the terms "criteria" and "alternatives." For our study, we rely on the terminology used by Malczewski (1999), Saaty (2008), and Yüzügüllü (2005).[lii,liii,liv] Key terms used in this research are: *goal*, *objectives*, *criteria*, *attributes*, *weights*, and *alternatives*. The rationality paradigm states that an individual who is making a decision is maximizing his/her utility/objective function.[lv] In the case of real-world decision-making, the objective function often is not defined, and a great degree of uncertainty exists. In this situation, the decision-maker tries to reach a goal, or a set of goals "as determined by a set of …targets…that are perhaps not the 'best' but are satisfactory and sufficient for the decision-making problem under consideration." If there is more than one such alternative, a decision-maker tries to choose the alternative that is preferred to others.[lvi]

The Webster dictionary defines a goal as "the end to which effort is directed."[lvii] González-Pachón and Romero (2010) suggest a mathematical expression for goal (g_i) $\quad f_i(X) + n_i - p_i = t_i$

where:

$f(X)$ is a function of the vector of decision variables

$f_i(X)$ is the i'th attribute of this function

t_i is the target value for i'th attribute, and

n_i and p_i are negative and positive deviations variables respectively.

A *goal* is the most general level in multi-criteria objectives hierarchy.[lviii] An *objective* is a more specific level; it defines both the desired state of the system and the direction of changes in one or more attributes that are needed to reach this desired state.[lix] An *attribute* is even more detailed; it is "a measurable quantity and quality associated with an object".[lx] A *criterion* is the "standard of judgment" used to measure the performance of alternatives towards objectives. A *weight* is an assigned attribute, a form of judgment about relative importance of objects, alternatives, and/or criteria. Weights are used to compare objects in a set with each other.[lxi,lxii] An *alternative* is "a decision or action variable."[lxiii] Metrics measures contributions of alternatives towards objectives. Figure 3 in the Appendix represents graphically the framework for MCDA.[lxiv,lxv]

In this project, the highest level goal is "Defense Mission." Lower level objectives include cost minimization, defense readiness, and environmental protection. The level of criteria contains, among others, base independence, cost of water systems, cost of wastewater systems, water quality and air emissions. There also will be even more detailed and lower levels of (secondary and tertiary) sub-criteria identified through the participation and information contribution by SMEs. The challenge of good objectives hierarchy design is that high-level broad goals are usually not well defined. In order to formulate the high-level goal, MCDA should identify specific lower-level criteria and objectives while keeping a balance between specificity and tractability.

5.2. Use of SMEs to Develop the Objectives Hierarchy

Group idea generation and structuring (GIGS) techniques are based on the premise that reality is always subjective to the person who experiences it, and as a rule is shared among several individuals "to give meaning to … interactions."[lxvi] Human judgment is subjective. In the case of strategic and large-scale decision-making, acting upon objective descriptions of reality rather than subjective judgment likely will produce outcomes to which more individuals can relate and be satisfied.

Combining judgments from several individuals ideally should produce relatively more objective descriptions of reality. Sometimes the convergence towards objective group vision does not happen, however, when one (or more) individuals in the selected group have unrealistic judgments. In order to avoid this non-convergence problem, the group should include individuals with as realistic (in researcher's point of view) judgment as possible.

Collecting data and knowledge from SMEs relies on several assumptions:

- SMEs have goals, objectives and criteria compatible and comparable with goals and criteria of vast majority of stakeholders (population);
- SMEs have collected and processed sufficient amount of data and information about "reality";
- SMEs already have formed a preference structure of some sort between goals, objectives, and criteria; and
- SMEs have assigned weights to criteria.[lxvii]

There are over a hundred techniques for group idea generation.[lxviii] Herring, Jones and Bailey (2009) developed the list of 19 idea generation categories: active search, attribute list, brainstorm, collaborate, concrete stimuli, critique, documenting, expert opinion, empathy/user research, encompass, forced analogy, incubate, passive searching, prototyping, reflect, role playing, sketching, socialize, storyboarding.[lxix]

The process and product of group idea generation can be recorded/documented or not. Documentation/recording can be done with "pen and paper" or using group support systems (GSS) technologies. Some researchers believe that, in certain cases, GSS technologies can help to generate more ideas and generate ideas of better quality or greater relevance.[lxx] Members of the group can be present in one location and work together, or can be individually adding their contribution to the process and review contributions of other group members in time and place of their choice.

Below are several of the most commonly used methods of group idea generating and structuring:

- Nominal Group Technique (Pros: generates many ideas. Cons: requires a meeting of group members; may never reach consensus)
- Interpretive Structural Modeling (ISM) (Pros: better understanding of relationships between criteria; does not require group meetings. Cons: "emphasis on qualitative structural aspects rather than numerical statistical properties."[lxxi])
- Delphi Method (Pros: generates many ideas; does not require group meetings, is time and cost efficient; Cons: may require several ranking iterations)

The choice of the best GIGS method for this research is defined by the type of data we need to collect and the constraints of the SMEs. It is reasonable to expect that our candidate SMEs will have tight schedules. This imposes several limitations on method selection. Preference should be given to methods that do not require SMEs to meet together in the same location, invest extensive amounts of time into the project, nor always be present in local area. A second requirement for the method is that it allows for a combination of quantitative and qualitative data. Based on these considerations, both ISM and the Delphi method have been determined be applicable for this research.

5.3. How the SME Interaction Process Works

For the purpose of this research, it will be most feasible to use a combination of secondary quantitative data and judgments of SMEs. While working with SMEs, the steps are: (1) set the context, (2) work with SMEs to specify objectives, primary/secondary/tertiary criteria, (3) identify alternatives/actions to meet these objectives, (4) develop the decision model, and (5) assess and test the decision model.[lxxii] Installation alternatives should be generated using the five net zero steps of reduction, re-purpose, recycling and composting, energy recovery and disposal.[lxxiii]

Keys to the successful study include careful selection of SMEs, organization of their effective participation in the study as a group, and clear communication of interview questions. There are three groups of people whose participation in this type of research can be useful: decision-makers, subject matter experts, and stakeholders. There is a certain degree of overlap among these three groups. For example, SMEs very often make strategic decisions; they can also be stakeholders if the decision outcome will affect them directly.[lxxiv] Normally, the MCDA begins with defining the problem. The next steps are: identifying the stakeholders, decision-makers, and SMEs; determining attributes and their relative importance/weights through group idea generating and structuring technique; and assigning values to the criteria to develop the decision model. The iterative nature of the process allows reaching consensus on prioritizing criteria and ranking alternatives.

Because of the breadth of definition of the research goal in our study, stakeholders will be numerous. Moreover, if we will be considering both national and OCONUS locations, involvement of all stakeholders may be impractical. Therefore, the primary focus should be given to decision-makers and SMEs who have expertise in both national and overseas conditions. The leading candidates for participation in the research will be experts in defense, experts in water infrastructure, water quality and efficiency, and experts in water rights. These candidate participants can be found in the following organizations: government and state offices, national laboratories, utility companies, environmental organizations, infrastructure developers, renewable energy financing companies (may be familiar with risks associated with net zero projects), consulting companies, international organizations, and universities.[lxxv]

We recommend conducting a test interview prior to the beginning of the actual first round of interviews. Test interviews should recruit representatives of the public sector (DoD in particular), the private sector, international organizations and universities. The interviewees do not necessarily need be same as the SMEs. This procedure will troubleshoot the questions and terminology, ensuring that everyone understands interview questions in the same manner.

Next, SMEs should be contacted with an invitation letter to participate in the research, with a follow-up call. Relevant literature stresses the benefits of face-to-face interviews rather than use of surveys. Therefore, use of face-to-face interviews is a preferred method of contacting SMEs, depending on their consent and availability. Several rounds of interviews should be conducted until consensus is reached on criteria and their weights.

5.4. Pros and Cons of the MCDA and SME approach

A valid question to ask is whether or not it is reasonable to make long-term policy and capital investments decisions based on opinions of subject matter experts. As most would agree, "the overall policy process is highly dynamic… it can change greatly over time as specific policy actors come and go" (Kraft, 2010).[lxxvi] An important point is that policy adjustments and change are normal and can be a desirable adaptation technique for changing conditions. At the same time, a decision maker may be cautious about investing in a project with a 30-year payback period if there is a risk that five years later the project will no longer align with updated policy goals, and thus all initial investments will become sunk costs. Judging from precedents in American policy-making, adopted policies almost never get terminated, although specific goals and timeframes can be adjusted over time.[lxxvii,lxxviii]

We can assume that SMEs with long and successful track records will well represent the mission of their organizations. Since organizational missions do not change often, views of SMEs will not be prone to rapid, frequent and drastic changes.

Another challenge is facilitating communication among members of the SME group. Ultimately the group of SMEs should be able to reach consensus about the structure and content of the objectives hierarchy.

From a methodological point of view, the weak side of the MCDA method is that the "multi-criteria problem is mathematically ill-defined."[lxxix] This happens because any specific option can be either superior or inferior compared to other available options, depending on the criteria we chosen for comparison/analysis.

6. MCDA Method: Objectives Hierarchy and Criteria Weighting

As shown on the Figure 2 in the Appendix (Polatidis et al., 2006), MCDA methods can be divided into two classes: methods using outranking technique, utility-based models and “other methods”.[lxxx]

The choice of structural form, and hence, of method, will depend on the type of data we will be using. Namely, if evidence of incomparability and incommensurability exists in the criteria, and if compensation among alternatives is present, then one of the outranking methods should be used. If all criteria will be commensurable and directly comparable (with each alternative having a single score), then a method from the family of utility-based models can be used. Prior to implementing the process described in this report, it is not possible to predict what type of data and information will be generated via the GIGS process (Delphi or ISM). Therefore, the MCDA method should be chosen once the initial round(s) of interviews are completed.

Other factors to be considered while selecting the most appropriate MCDA method include ease of use, clarity of the process and procedures, validity and reliability, minimal number of restrictive assumptions, software availability and cost.[lxxxi] At the data collection stage, we also want to keep in mind computational tractability of our model. The number of selected criteria, as well as the number of levels of criteria and sub criteria (primary, secondary, etc.), should provide sufficient detail in the objectives hierarchy while not being so numerous as to make computations too complex. Ideally we want to develop a model that which is specific, comprehensive, and relatively simple.

After studying and comparing all relevant MCDA methods, we have selected two for use in developing a multi-criteria model to support NZW decisions for DoD installations. Either of these methods will enable decision makers to identify preferred alternatives based on the input parameters acquired from the SME group. One of the two recommended methods is the PROMETHEE method, which uses an outranking procedure. The second recommended method is the utility-based benefit-cost Analytic Hierarchy Process (AHP) method. These methods have been tested and assessed in MCDA studies similar to that of the net zero water challenge. A brief description of each method is provided below. More details can be found in the original papers by Giannopoulos and Founti (2010), and Saaty and Sodenkamp (2008).[lxxxii,lxxxiii]

6.1. PROMETHEE Multi-Criteria Method

The Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE) was developed to incorporate uncertainty and qualitative data into decision-making process.[lxxxiv,lxxxv] While economic variables (such as, for example, benefits and costs) and many environmental variables are measured in via cardinal scales, combining them with social and political qualitative observations is a complex task. Qualitative data on social and political factors can be measured via ordinal scales, or can be left in incommensurable (incomparable) forms.

The PROMETHEE method is rooted in the theory of fuzzy sets developed by Zadeh (1965).[lxxxvi] This method addresses the issue of data incomparability and incommensurability by pairing alternatives and comparing them to each other in order to derive criteria preference functions. PROMETHEE will be appropriate for our study if during the group idea generation and structuring stage (Delphi or ISM) both quantitative and qualitative and incomparable/incommensurable data are collected.

The steps of the PROMETHEE method are the following. First, we define the alternatives and criteria:

$A = \{a_1,...,a_J)$ is a set of discrete alternatives $a_j (j = 1,...,J)$

$C = \{c_1,...,c_I)$ is a set of criteria $c_i (i = 1,...,I)$

Next, we construct a decision matrix (DM), where each element $c_i(a_j)$ is a "rating" of an alternative – the value of *j*'s alternative performance relative to *i*'s criteria:

$$DM = \begin{pmatrix} c_1(a_1) & \cdots & c_1(a_J) \\ \vdots & \ddots & \vdots \\ c_I(a_1) & \cdots & c_I(a_J) \end{pmatrix}$$

Next, we compare pair wise ratings of all alternatives associated with each criterion c_i, and find the difference in alternative ratings for each pair:

$c_i(a_j) - c_i(a_{j'}) = d^{j,j'}$, here $c_i(a_j)$ and $c_i(a_{j'})$ are two different elements of the DM matrix.

Finally, we define the "preference function" for each criterion c_i: $P_i(d_i^{j,j'}) \in [0,1]$

The preference function can be used to estimate the degree of alternative preference and selection of the best alternative as follows:

1) Indifference between alternatives $a_j, a_{j'}$: $P_i(d_i^{j,j'}) = P_i(a_j, a_{j'}) = 0$

2) Weak preference of alternative a_j over alternative $a_{j'}$: $P_i(d_i^{j,j'}) = P_i(a_j, a_{j'}) \sim 0$

3) Strong preference of alternative a_j over alternative $a_{j'}$: $P_i(d_i^{j,j'}) = P_i(a_j, a_{j'}) \sim 1$

4) Strict preference of alternative a_j over alternative $a_{j'}$: $P_i(d_i^{j,j'}) = P_i(a_j, a_{j'}) = 1$

More information on this method and model development can be found in the paper by Giannopoulos and Founti (2010).[lxxxvii]

6.2. The Cost-Benefit Analytical Hierarchy and Analytical Network Method

The class of MCDA utility-based methods includes simple additive weighting (SAW), the analytical hierarchy process (AHP), the multi-attribute utility theory (MAUT) group of methods, the Simple Multi-Attribute Rated Technique (SMART), as well as others.[lxxxviii, lxxxix] These methods deal with problems where all criteria are directly comparable and commensurable and there is compensation among alternatives such that "a relatively good performance of an action to one criterion can totally offset a relatively bad performance on some other criteria."[xc]

Cost-benefit analysis is often used in decision making to compare alternatives. Application of cost-benefit analysis to MCDA can be particularly useful and relevant when dealing with long-term planning, such as is the case with water management.[xci] This method creates a "common denominator" among the set of available alternatives, thus allowing identification of the utility maximizing option.[xcii]

If the data collected allow using utility-based method, we recommend use of the benefit-cost analytic hierarchy process (AHP) model developed by Saaty and Sodenkamp (2008).[xciii] This method develops two hierarchies: one for benefits and the other for costs. In each of these two hierarchies there are identical sets of alternatives. Each alternative is connected to all lowest level criteria within the hierarchy. The SMEs are asked to rank the priority of each criterion, as well as the priority of each alternative for this criterion, as a cost determinant and as a benefit determinant. Next, the total rank of each alternative is estimated within each hierarchy to identify the alternative with the highest benefit rank and the alternative with highest cost rank. Finally, the ratio of "benefit rank of alternative" to "cost rank of alternative" is estimated for each alternative. It also is possible to estimate the marginal cost-benefit ratios for each alternative to decide the allocations of additional resources that would generate the greatest marginal returns.[xciv] Schematic representation of this method is provided in the Appendix, Figure 4.

7. Recommended Next Steps

We view the development of the multiobjective benefit-cost framework for the analyses of net zero water alternatives set forth in this report to be the first of three phases necessary for making maximum use of this approach in facilitating the identification of optimal alternatives (portfolios of alternatives) for the six net zero water pilot installations. We recommend that consideration be given to continuing this research via the following additional research phases:

Phase II – Implementation of the multiobjective benefit-cost framework described herein at selected net zero water installation(s).

Phase III – Comparisons of the results of Phase II investigations to analyses of net zero water opportunities at one or both of the single integrated net zero installations, in order to identify and quantify trade-offs among net zero water, net zero waste and net zero energy that exist at the installation level.

Appendix

Figure 1. Decision making.[xcv]

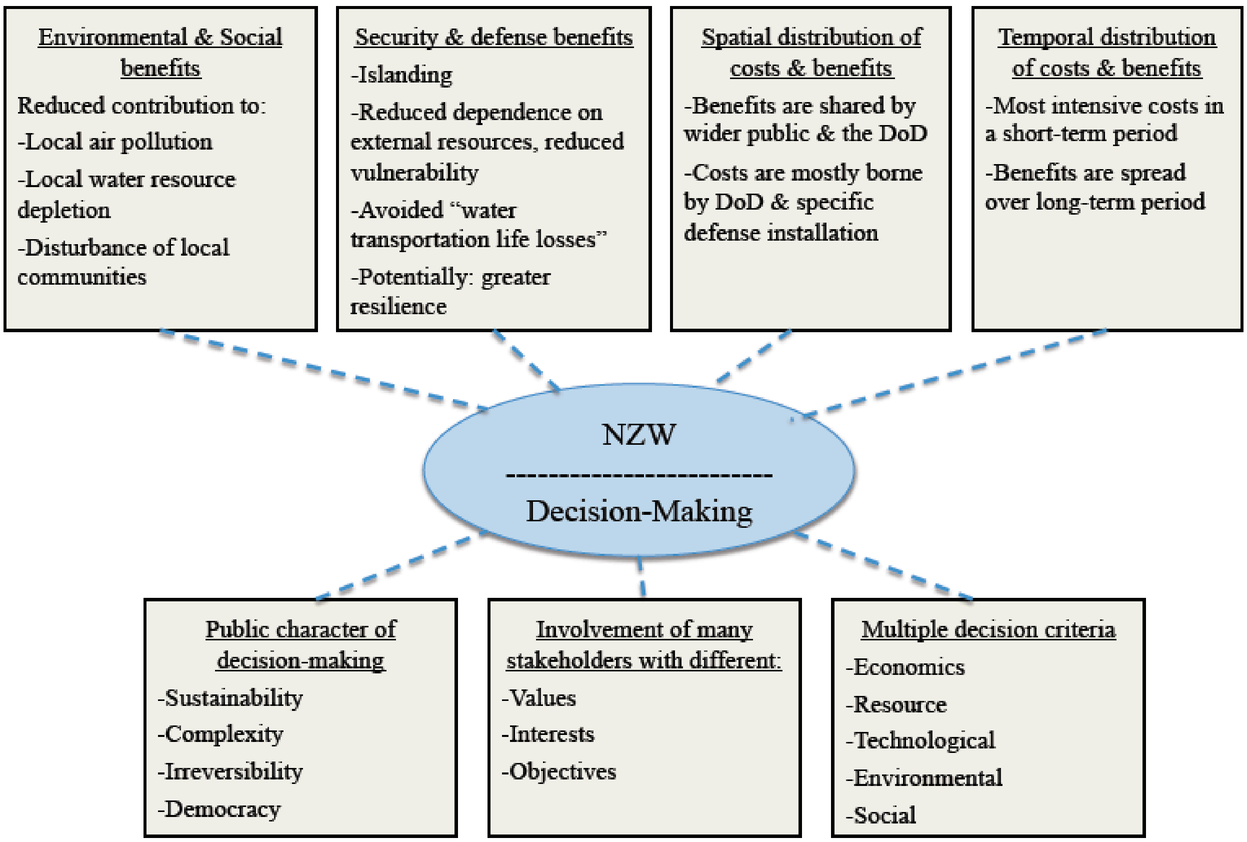


Figure 2. Multi-criteria methods.[xcvi]

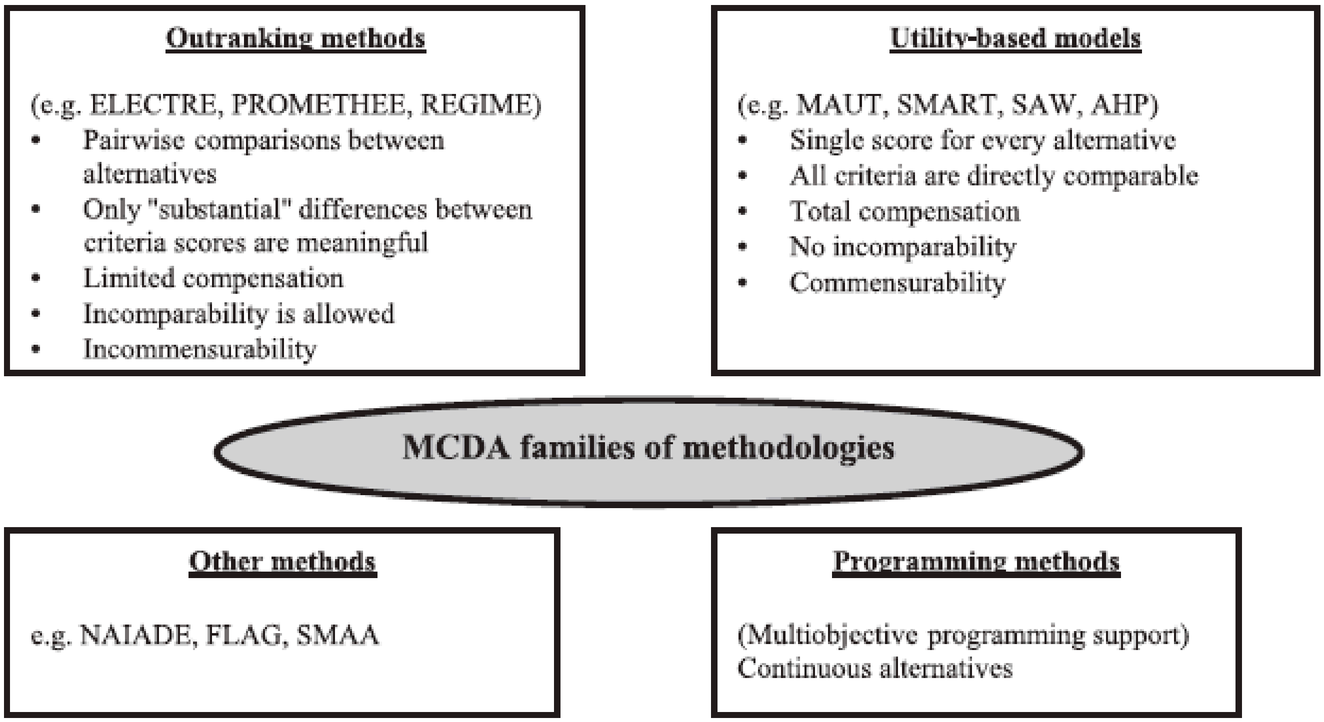
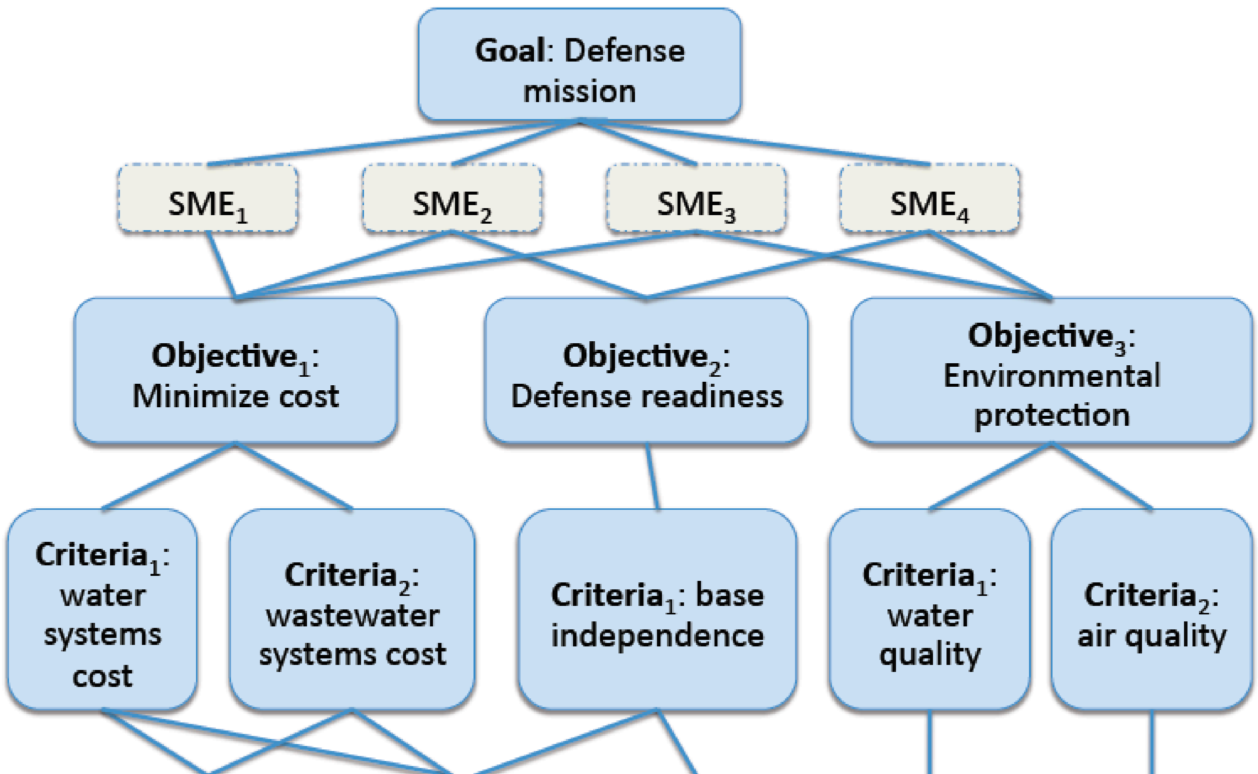


Figure 3. Sample* MCDA framework for the case of incommensurable** alternatives.



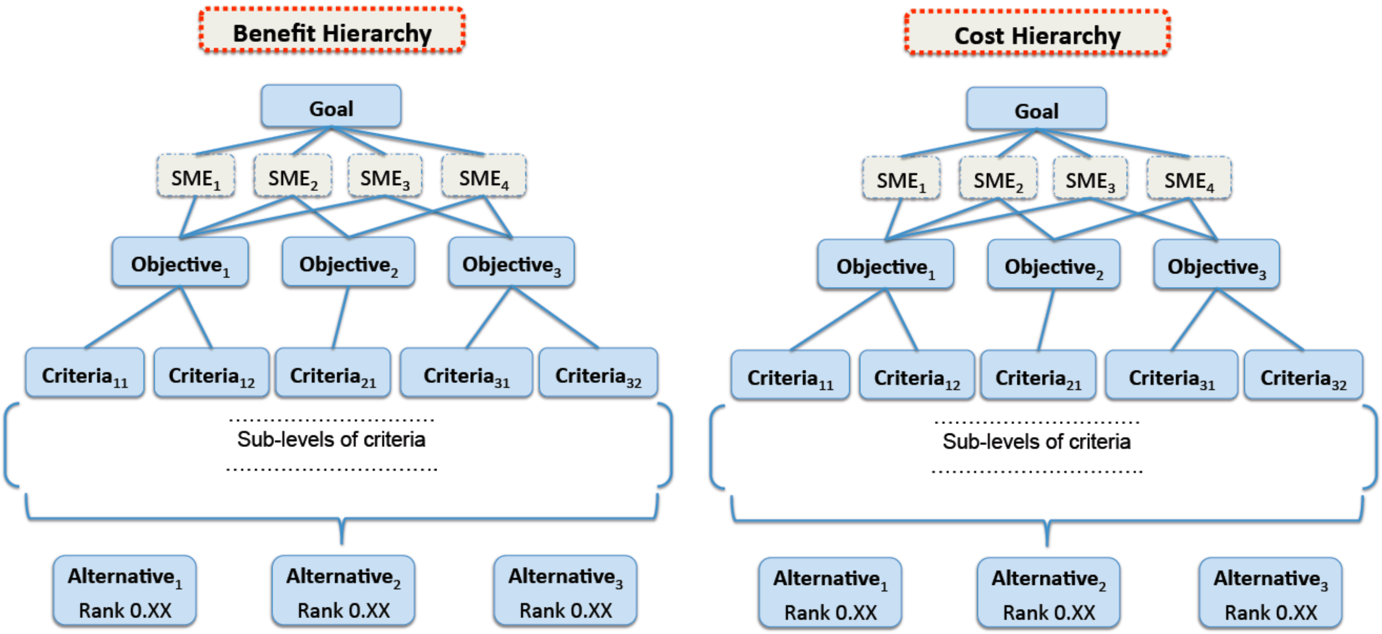
	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Attribute 5
Alternative 1	Outcome $_{11}$	Outcome $_{12}$	Outcome $_{13}$	Outcome $_{14}$	Outcome $_{15}$
Alternative 2	Outcome $_{21}$	Outcome $_{22}$	Outcome $_{23}$	Outcome $_{24}$	Outcome $_{25}$
Alternative 3	Outcome $_{31}$	Outcome $_{32}$	Outcome $_{33}$	Outcome $_{34}$	Outcome $_{35}$

* The actual hierarchy will be developed through Delphi method interaction with SMEs.

** In the problem with commensurable and comparable alternatives all lowest level criteria will be connected to every alternative.

There can be more than one level of criteria; each lower level adds specificity to model.

Figure 4. Benefit-cost analytic hierarchy process.[xcvii]



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