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USING MAVT TO INCORPORATE PUBLIC PERCEPTION WHEN CHOOSING A NUCLEAR FUEL CYCLE

Stephen Clement

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USING MAVT TO INCORPORATE PUBLIC PERCEPTION WHEN CHOOSING
A NUCLEAR FUEL CYCLE

A thesis submitted in partial fulfillment of the requirements for the degree of Master
of Science at Virginia Commonwealth University.

by

STEPHEN CLEMENT

Bachelor of Science - August 2007 to December 2011

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Abstract

USING MAVT TO INCORPORATE PUBLIC PERCEPTION WHEN CHOOSING A NUCLEAR FUEL CYCLE

By Stephen Clement

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2016.

Director: Dr. Sama Bilbao y León,
Associate Professor and Director of Nuclear Engineering Programs, Department of Mechanical and Nuclear Engineering

Nuclear energy is a source of carbon free power. With many countries striving to make deep carbon cuts in their energy sectors, nuclear energy could be a large part of the solution. One of the main obstacles standing in the way of the use of nuclear energy is the issue of used nuclear fuel disposal. According to the Nuclear Energy Institute, the U.S. creates about 2000 metric tons of used nuclear fuel per year and has generated around 76,000 metric tons of used nuclear fuel over the last 4 decades. While there are technical problems that need to be solved, it is primarily the public and political opposition to the disposal of used nuclear fuel that stands in the way of progress in this area. This work attempts to address this issue through the use of Multi-Criteria Decision Analysis (MCDA). In order to make a decision among ten different fuel cycles, we have brought together the following five stakeholders: Nuclear Scientists and Engineers, Environmental Scientists, Economists, Political Scientists, and The General Public. Using Multi-Attribute Value Theory (MAVT), we have been
able to develop decision models for each stakeholder as well as a model that combines them all and came to the conclusion that of the ten fuel cycles considered, the best decision is to continue to use On Site Dry Cask Storage. This is a decision made with small sample sizes but the methodology could be applied at much larger scales and can potentially be used to choose a fuel cycle that encounters much less political and social opposition to its implementation.
CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

This section will provide a brief overview of the scope of the problem as well as context for the work.

1.1.1 Nuclear Power

Currently, nuclear power accounts for around 20% of the electricity generated in the United States and there are 100 reactors in operation with 4 more being built. Nuclear power plants work the same way as any other conventional thermal power plant. Water is heated into steam, spins a turbine which spins a generator, and electricity is generated. Nuclear power plants stand out due to where the heat to create the steam comes from; fission of uranium atoms. This project is concerned with implementing a nuclear fuel cycle for the United States.

The phrase “nuclear fuel cycle” refers to the life cycle of the fuel used in a nuclear reactor from cradle to grave. An illustration from of the nuclear fuel cycle is shown in figure 1. The fuel cycle is broken into the “front end”, before the energy production, “back end”, after the energy production. The front end consists of what needs to be done to prepare the raw material for use in a power plant. The back end consists of what needs to be done to properly manage and dispose of any byproducts from the energy generation. The processes are briefly outlined below.

Uranium is mined from the earth and retrieved as Uranium Oxides (primarily U₃O₈). Eventually it will be turned into a fuel, typically Uranium Dioxide (UO₂)
which will be “burnt” in a reactor. Before the Uranium can be made into fuel, however, it needs to be enriched. Naturally occurring Uranium is 0.7% U$^{235}$ and 99.3% U$^{238}$. The U$^{235}$ is fissile, meaning it can be broken by a thermal neutron, and generate heat for the power plant. In order to have enough U$^{235}$ present in the fuel to sustain the nuclear reaction, the uranium must be enriched to a higher concentration than occurs naturally. This enrichment process starts by converting the uranium oxides to Uranium Hexafluoride (UF$_6$). Through the use of gas centrifuges, the UF$_6$ is enriched to between 3% and 5% for light water reactors. Laser enrichment has also been considered [4]. It is this enriched uranium that is turned into fuel. Nowadays, reactors use a ceramic uranium dioxide (UO$_2$) as the fuel. Small pellets are loaded into fuel rods and loaded into the reactor. The U-235 undergoes fission, releasing energy to be used by the power plant to generate electricity along with fission products. The nuclear fuel is used in the reactor for 3 operating cycles, or about 3.5 years. Although it still has quite a lot of potential fuel in it, it is at this point considered “used up”
and is removed from the reactor. Because the fuel is now radioactive, it is placed in spent fuel pools to undergo thermal cooling for a period of 5 to 10 years before being removed and stored in dry casks on site.

1.1.2 Used Fuel Disposal

The fission of uranium leaves fission fragments as well as neutrons behind. These neutrons drive the fission process but can also activate other elements in the fuel cladding or impurities in the fuel itself. These activated elements along with the fission products and leftover fuel are all part of the used fuel that exits the reactor [5].

As the fuel undergoes decay, its radioactivity decreases. The NRC requires that the fuel be stored safely away from humans and the environment until the activity of the fuel matches that of the ore that it was mined from. Figure 2 shows the decay of used nuclear fuel. As can be seen, the activity of the fuel in the first hundred years is dominated by the fission and activation products. These then decay away and the remaining activity of the fuel is dominated by the actinides. Without recycling or reprocessing, the waste will need to be stored for around 100,000 years as shown in figure 2.

The Nuclear Energy Institute (NEI) estimates that the U.S. creates around 2,000 metric tons of used nuclear fuel per year and has accumulated around 76,000 metric tons of used nuclear fuel over the last 4 decades [6]. When talking about used fuel disposal, there are two types of fuel cycles: open and closed. An open fuel cycle, also called a once through fuel cycle, has the uranium exiting the reactor, going to storage and then straight to repository where it will be left for thousands of years or possibly used in future fast breeder reactors [7]. A partially closed fuel cycle involves recycling and reprocessing the used fuel to increase uranium utilisation [7]. Current methods of
reprocessing involve the PUREX process where uranium and plutonium are separated from the used fuel and fabricated into new mixed oxide fuel (MOX) [7]. This method does not significantly decrease the long-term toxicity of the remaining high-level waste [7]. A fully closed fuel cycle which could allow close to 100% uranium utilisation would be the implementation of a fast reactor [7]. Not only would the utilisation of uranium be significantly higher, the long lived actinides present in PWR waste could be significantly reduced as they are “burnt” in a fast reactor along with the uranium [7]. This gives the advantage of decreasing the long-term toxicity of the used nuclear fuel.

Currently, in the United States, the used nuclear fuel is held in cooling pools and/or in concrete casks at the reactor sites as a sort of interim storage. Under current law the US DOE takes ownership of the used nuclear fuel once it is discharged from the core and is supposed to collect it and transport it to a permanent geological repository. This same law, the Nuclear Waste Policy Act of 1982 (amended in 1987),
selected Yucca Mountain as the only potential site for the permanent repository and created the Nuclear Waste Fund to which utilities have been contributing 0.1 cents per Kwh since then. It is here where nuclear energy moves from science to politics.

1.2 Used Nuclear Fuel Politics

Nuclear waste is governed by the Nuclear Waste Policy Act (NWPA). The NWPA was passed to address issues of the growing shortage of space in used nuclear fuel storage pools and the fact that no state wanted to hold a used nuclear fuel repository. When the NWPA was passed in 1982, it gave the DOE the responsibility of disposing of the used nuclear fuel being held on site at operating reactors. In order to cover the cost of this responsibility, the utilities were obligated to pay 0.1 cent per kilowatt hour to the DOE.

To address the issue that no state wanted a repository, the NWPA sought to use a congressional mandate for the placement of repositories. In the spirit of fairness, two repositories would be built so as to not place the burden of the entire United States’ used nuclear fuel on one state. In addition to the 2 repositories, the DOE was contractually obligated to remove the used nuclear fuel from reactor cites by 1998, propose a site for a monitored retrievable storage (MRS), and gave the NRC responsibility for licensing the aforementioned facilities. By 1986 efforts to have repositories in Washington State, Texas, and Nevada were being strongly opposed from state officials. At this time, the DOE announced it was suspending efforts to identify a second repository citing rising costs and lower projections of nuclear waste. This along with the acknowledgement of original timelines and cost estimates of the NWPA being unrealistic, lead to an amendment to the NWPA in 1987.

The 1987 amendment to the NWPA officially named the Yucca Mountain site in Nevada as the only site being considered for the geologic repository in the hopes that
the state of Nevada would acquiesce \[9\]. This bit of legislation gained the affectionate nickname of the “Screw Nevada” bill. In order to overcome the states’ objection, congress included a possible $20 million per year for hosting a repository and a $10 million per year for hosting an MRS site \[9\].

After $15 billion were invested into research and the construction of exploratory tunnels toward the use of Yucca Mountain as a repository, it was defunded for political reasons. Senator Harry Ried of Nevada (who has been replaced in 2016 by Senator Catherine Cortez Masto who holds a similar view) was massively opposed to having the repository built and through his political maneuvering, he was able to have President Obama defund the Yucca Mountain project\[9\]. With the promise of the used nuclear fuel being picked up by the DOE in 1998 not being fulfilled, the utilities sued to no longer pay the 0.1 cents required as per the NWPA in 2013 and won \[8\]. After the 2016 election of President Trump, it is uncertain as to whether the White House’s position on Yucca Mountain will be maintained. In the meantime, the DOE is pursuing consent based site selection for a waste repository in order to gain the public’s support \[9\].

On a broader scale, the politics of climate change also affect nuclear power. On August 3, 2015 the Environmental Protection Agency (EPA) released the final version of the Clean Power Plan (CPP) rule which imposes national limits on the carbon pollution emitted from existing fossil fuel plants \[10\]. The CPP rule was contested by 24 states on February 9, 2016, and the Supreme Court stayed implementation of the rule pending judicial review. These goals are not limited to the U.S. In December 2015, the United Nations Climate Change Conference, Conference of the Parties 21 was held in Paris, France. By signing the Paris Agreement, most countries of the world agreed to serious national measures towards keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts
to limit the temperature increase even further to 1.5 degrees Celsius [11] [?]. The Paris Agreement entered into force on 4 November 2016 and currently 111 countries out of the 197 members of the Convention have ratified, including the USA and China. The Paris Agreement explicitly considers nuclear power as one of the technologies capable to help achieve these goals [11].

Politics are subject to people’s beliefs. These beliefs can be based on fact or feelings and, in either case, carry just as much weight. Nuclear energy has a large negative stigma associated with it. Many people associate the word “nuclear” with the devastation of Hiroshima and Nagasaki or with a fear of radiation. For other people, “nuclear” may bring to mind a clean energy source or medical science. In order to implement a nuclear fuel cycle for the United States, one has to balance the views of the people impacted by the decision. Without solving the issue of competing views, we are unable to implement a method of addressing the issue of used nuclear fuel disposal.

1.3 Goal

This work is a smaller part of a larger project called Rebranding the Nuclear Fuel Cycle supported by the DOE and NEUP. The overall objective of the project is to devise an effective communications strategy for the US nuclear fuel cycle to reach the appropriate stakeholders and facilitate stakeholders understanding of the relevant issues. There are three main parts of this project and they are all intimately intertwined and are listed below [12].

1. In-depth market research study to identify and understand the relevant stakeholder populations; the opinion trends and influences they display; their perception of risk and risk tolerance; their environmental and social equity sensitivity; their views on the appropriate balance between technology, human development
and the environment; as well as their individual priorities, concerns and wants.

2. Application of Multi-Criteria Decision Analysis (MCDA) theory to systematically compare, select, or rank a set of technical alternatives for the nuclear fuel cycle. This analysis will incorporate the information gathered in the above market research study as a key input. The outcome of the MCDA will be the proposal of a technical strategy or a combination of strategies that best addresses the concerns and the expectations of the relevant stakeholders.

3. Development of a branding strategy and a communications plan for the technical strategy selected through the MCDA.

The work outlined in this thesis is primarily referring to the first and second objectives listed above but must be viewed in the broader context of the Rebranding project. This is not the first time decision analysis is to be used in the realm of the nuclear fuel cycle. In 1994, Ralph Keeney and Detlof von Winterfeldt undertook an assessment of Yucca Mountain as a repository along with two other alternatives, a centralized monitored retrieval storage facility (MRS) and a continuation of dry cask storage on site [13]. Our work differs in that rather than addressing the issue from a strictly technical standpoint, we are looking at the quasi-rational beliefs of five different stakeholders. Our intent, as stated above, is to look at the beliefs of these stakeholders and how they may choose among 10 different fuel cycles, and combine these beliefs in a way to propose a fuel cycle that will properly address the concerns of each stakeholder.
CHAPTER 2

DECISION ANALYSIS

Decision analysis aims to help people make better decisions more often through providing a structured approach to decisions that have complex with many competing objectives. Ralph Keeney calls it “a formalization of common sense for decision problems which are too complex for informal use of common sense.” \[14\]. There are four components to decision analysis: structuring the decision problem, assessing the impacts of each alternative, determining the values of the decision makers, and evaluating and comparing alternatives \[14\]. To better illustrate decision analysis, a running example will be developed through this chapter, the decision among jobs.

During the course of this project, different methodologies were considered, the Analytical Hierarchy Process (AHP) and Multi-Attribute Value Theory (MAVT). The similarities and differences between these methodologies will be discussed in respect to the four steps of decision analysis below. Ultimately, we chose to use MAVT over AHP for the reasons discussed below.

2.1 Structure of the Decision Problem

Structuring the decision problem sets the tone for the rest of the decision analysis process, so much care must be taken in doing this correctly. This process is identical for both MAVT and AHP. Structuring the decision problem involves generating possible solutions (alternatives) to the problem, as well as objectives that one hopes to achieve through making this decision. We will be using the example of “Selecting the Optimum Job.” Decision analysis would ask a decision maker to come up with
not only reasonable jobs like banker, salesman, teacher, but also seemingly outlandish ones like astronaut or President of the United States. One should also consider the worst alternatives they can think of such as toll taker or sewer cleaner. The reason is not because they are probable alternatives, but they reveal some objectives that we may have when it comes to the decision. In the previous examples, objectives of maximizing power or minimizing monotony might be brought out. Eventually the alternatives are whittled down to what seems reasonable. In our example, let’s call them Job A and Job B.

2.1.1 Objectives

The objectives of a decision are structured from what you hope to accomplish from the decision. A good set of objectives must pass the clarity test. The clarity test attempts to address problems of not properly defining objectives and their ranges in such a way that they can be answered [15]. The clarity test is conducted by imagining a clairvoyant is assessing the objectives. Having knowledge of all future events, they
should be able to give values for every objective. In order to pass the clarity test, it is important that the objectives be monotonic, fundamental, and have defined ranges and measures. It is also important that the objectives be mutually exclusive and collectively exhaustive. While these are not collectively exhaustive, for our example decision we will consider the objectives of Maximize Salary, Minimize Traffic During the Commute and Maximize Meaningful Contributions.

A monotonic objective is structured such that as the measure of the objective increases or decreases, the value the objective has to the decision maker increases or decreases. The value function doesn’t have a local maximum or minimum. If it does, the objective is made up of two monotonic objectives [16]. When looking at the example objective of Maximize Salary, the larger the salary is, the more value the decision maker would get out of it. The maximum is at one end of the range and the minimum is at the other. Figure 9 shows an example value function to be discussed later.

Objectives can fall into three categories: means objectives, fundamental objectives, and strategic objectives. A means objective is one that is a means to an end (that end usually being a fundamental objective). A fundamental objective is one that has inherent value and is affected by only the decision at hand [17]. A strategic objective is too broad to be affected by only the decision at hand and may be a broader goal of a company or set of stakeholders. To properly structure a decision, one must make sure that the objectives being considered are fundamental. If they are means objectives, the decision space will be too constricted and if they are strategic, the decision space will be too broad. An example of movement from a means objective through a strategic objective is shown in figure 4 through the lens of our example and the objective dealing with the commute.

If we were to use the means objective of Minimize Traffic, we would be missing
out on the importance of having minimal traffic. Consider an alternative that had a commute time of 4 hours but zero traffic. A decision model based on minimizing traffic would award the maximum amount of points to that alternative under this objective but the decision maker would not be happy with the commute. Minimizing traffic is a means to a shorter commute time.

One way to move to the right in the figure is by asking “Why is that important?” The reason the decision maker wants to minimize traffic is so the commute is short. In our case, Minimizing Commute Time is the fundamental objective. One can go too far though. If we move one further, Minimizing Commute Time may be important in Maximizing Happiness. The problem with using this objective in our decision is there is much more to happiness than choosing the right job. Being healthy, having good interpersonal relationships, and having hobbies are just a few other parts of happiness in addition to having the right job. Maximizing happiness is a \textit{strategic} objective. There is more to it than just this decision so it is outside the scope of this decision. To move back to the fundamental objective, one can ask “How is this accomplished?”
Table 1.: Hypothetical Examples Emphasizing Importance of Range

<table>
<thead>
<tr>
<th>Job</th>
<th>Salary</th>
<th>Commute Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$50,000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>B</td>
<td>$50,010</td>
<td>60 minutes</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Job</th>
<th>Salary</th>
<th>Commute Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$50,000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>B</td>
<td>$100,000</td>
<td>12 minutes</td>
</tr>
</tbody>
</table>

Through this question and “Why is that important”, a decision analyst can make sure the objectives in the model are all fundamental; not too specific as to miss the point and not too broad as to be affected by more than the decision at hand.

2.2 Assessing Impacts of Each Alternative

The importance of assessing the impacts of the alternatives allows us to compare how alternatives can score on each objective. Like the structuring of the decision problem, AHP and MAVT do not differ. One needs to do research to find possible values for the alternative on each objective. The possible objective values need to have upper and lower limits to consider. Not only will this help with the clarity test, but it will allow us to accurately weight objectives. Using our example of choosing between Job A and Job B, let’s say we are weighting Salary and Commute Time. Which objective should have more weight? Well, it depends on the range. Consider the two scenarios shown in table 1 dealing with salary and commute time. Assume Meaningful Contribution for both jobs to be identical in these cases.

The two scenarios above illustrate how important it is to know the range of possible values your objectives can take before you assess the weights for those objective. One would probably weight the commute time much more heavily than the salary in Scenario 1 while the opposite would probably be true for Scenario 2.

The objectives of Salary and Commute Time have natural measures of dollars and
minutes respectively. When we talk about objectives like Meaningful Contributions, we need to sometimes use a constructed scale. A well known constructed scale is that of “the pain scale” that might be used in an emergency room. A patient is asked to give a number between 1 and 10 to describe their pain level. A 1 or 10 may be different from person to person but it allows us some sort of insight to how the person is feeling. Using constructed scales allows a decision analyst to obtain values for objectives used in the model that do not have natural measures.

In addition to being natural or constructed, a measurement scale may be direct or indirect. A direct measurement directly describes the objective and is what we would use for Commute Time and Salary. An indirect measure would be using Employee Satisfaction as a measure for Meaningful Contributions. While there may be more objectives playing into Employee Satisfaction than Meaningful Contributions, that may be the best way we can get a feel for if the employees feel they are making Meaningful Contributions to their work. The best measurements are direct and natural and the worst being indirect and constructed. All are better than having no measure and excluding an important objective. With objectives decided on, the structure of the decision is usually represented as a hierarchy of objectives. A simple hierarchy for our example is shown in figure 5. The structuring of the decision problem has given us the hierarchy of objectives, as well as table 1.

2.3 Determining Values of Decision Makers

Every decision is subject to the preferences/priorities of the stakeholders involved in the decision. What one person thinks is a good job differs from someone else’s idea of a good job for a variety of reasons. Decision analysis addresses these differences by allowing stakeholders to apply weights to different objectives of the decision. These preferences/priorities are what will drive the decision. The stakeholders are not really
choosing among alternatives. They are defining their personal values and using the decision model, we can choose an alternative that best fits their values. It is in this section that AHP and MAVT differ. We will start with AHP.

The Analytical Hierarchy Process (AHP) was developed by John Saaty (Saaty 1977 and 1994). The appeal for the use of AHP is that it revolves around pairwise comparisons of the decision criteria. Consider an example of choosing between three objectives; Maximize Salary, Minimize Commute, and Maximize Meaningful Contributions. An expert or stakeholder might be asked questions similar to those shown in Table 2. It is important that the stakeholder responding understand the the ranges associated with each objective they are considering as discussed in §2.2.

In addition to being relatively simple questions to ask, AHP allows for quantitative consideration of qualitative answers; the type of answer the General Public
Table 3.: Numerical Scales Used for Interpreting Qualitative Judgments

<table>
<thead>
<tr>
<th>How much more preferred?</th>
<th>Integer</th>
<th>Balanced</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal Preference</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Slightly</td>
<td>2</td>
<td>1.22</td>
<td>1.32</td>
</tr>
<tr>
<td>Moderately</td>
<td>3</td>
<td>1.5</td>
<td>1.73</td>
</tr>
<tr>
<td>Strongly</td>
<td>5</td>
<td>2.33</td>
<td>3</td>
</tr>
<tr>
<td>Very Strongly</td>
<td>7</td>
<td>4</td>
<td>5.20</td>
</tr>
<tr>
<td>Extremely</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

might find easier to give. To convert from qualitative to quantitative analysis, AHP uses one of the following interpretations shown in table 3. To better illustrate how these scales can affect the model, figure 6 has been included to show a graphical interpretation of table 3.

The disadvantage with AHP is that illogical rank reversal is possible. Consider three hypothetical objectives: A, B, and C. A respondent might say that $A > B$ and that $B > C$ but then might claim $C > A$. This, simply put, is illogical. While it might seem like a difficult mistake to make when only three questions are asked, the number of questions needed to be asked follows the following function.

$$N = \frac{n(n-1)}{2}$$

where $N$ is the number of questions one would need to ask to get a complete picture of the stakeholder’s feelings and $n$ is the number of objectives being evaluated. For a decision model with 10 competing objectives, 45 questions would need to be asked to get all the weights. This allows ample opportunity for illogical rank reversal. It is for this reason, we chose to use MAVT.
Fig. 6.: Graphical Interpretation of AHP Scales [1]
MAVT does not allow for the rank reversal inconsistencies like AHP. With MAVT, every objective in the same level of the decision hierarchy is evaluated at the same time using a method called swing weighting and through the use of Single Dimensional Value Functions (SDVF).

Considering our job example again, we have three objectives: *Maximize salary*, *Minimize Commute Time*, and *Maximize Meaningful Contributions*. To weight these, we imagine a hypothetical alternative that is the worst value in the proposed ranges of each of those categories. The stakeholder is then asked which value, if swung to its maximum, would make the largest improvement in value for the decision. That objective gets the maximum weight, say 10. The decision maker is then asked which objective would make the next largest improvement and is asked to weight that relative to the first objective they chose. A value of 10 would show equal importance to the first and a value of 0 would show no importance whatsoever. This process continues until every objective has a value. The weights are then calculated using equation (2.2). Table 4 shows an example. To walk through the example, a total of 21 points were awarded. To find the weight of any given objective, the points awarded for the objective in question will be divided by 21. When *Salary* was swung to its maximum value, for example, it received 9 points. That means the weight for *Salary* is \( \frac{9}{21} = 0.43 \). This process is continued for all the objectives in question.

\[
\text{Weight of objective} = \frac{\text{Points awarded to objective}}{\text{Total points awarded}} \tag{2.2}
\]

In addition to stakeholders’ differing opinions on how objectives should be weighted, they also have different opinions on how the alternatives should be scored on the objectives. Value functions allow us to take these differences into account in the model. An example that may be helpful to consider is to look at the value of monetary costs.
when it comes to two different people. Let’s consider an example of buying a car where our costs range from $10,000 to $15,000. We will consider Person A having $13,000 and Person B having $30,000 to spend on a car. It is clear that the way they look at spending money on the car may be different. Their value functions for the cost of the cars are shown in figures 7 and 8.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Salary</th>
<th>Commute</th>
<th>Contributions</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Available Commute</td>
<td>$50k</td>
<td>0hrs</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Best Available Salary</td>
<td>$80k</td>
<td>1 Hrs</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Best Available Contribution</td>
<td>$50k</td>
<td>1hrs</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Hypothetical Worst</td>
<td>$50k</td>
<td>1hrs</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weights</td>
<td>0.43</td>
<td>0.10</td>
<td>0.47</td>
<td></td>
</tr>
</tbody>
</table>
It is important to note that the best scenario gets a value of 100 (or any arbitrary value) while the worst scenario gets a value of 0. What we are interested in here is how the function looks between these values. As shown in figure 7 and figure 8, Person A and Person B have different attitudes towards spending their money on cars. Person A shows that they are less comfortable with spending money on the cars by having a steeper slope as the costs increase. They also cannot afford the more expensive option so the value of $14,000 and $15,000 are the same. They are out of the price range available to Person A. Person B on the other hand doesn’t mind spending these
amounts of money and that is shown by the value of most options being relatively high.

A value function is elicited similarly to how a swing weight is elicited. The stakeholder is asked to compare portions of the graph as to their value to them. The graph is broken down into smaller and smaller pieces to get the desired resolution for the function. Some example value functions are included in figures 9, 10, and 11 to further our example of choosing a job. Notice that the value functions cover the entire range of each objective and that the functions are monotonic.

The general trends of a person’s values can be seen in figures 9, 10, and 11. Figure 9 shows marginal utility which is usually present in gains or loss in money. Figure 10 shows that this person is fine with a 20 minute commute but after that, they have a significant loss in value up to 40 minutes. From 40 minutes on, they don’t seem to care too much as it is already bad. An alternative with a commute of 40 minutes or greater will be penalized with a low score. Figure 11 shows a linear trend meaning the bump from 0 to 1 in the Meaningful Contribution Rating is as important as as the bump from 9 to 10.

An addition use of value function is that it allows all the objectives to be compared using the same measure: value. It is difficult to say what a dollar of your salary is worth in Meaningful Contributions made to your company or society. By using a value function, we are comparing the value that one branch has to a stakeholder to the value of another branch to that same stakeholder.

2.4 Evaluating and Comparing Alternatives

Having structured the decision, assessed the impacts of the alternatives, and evaluated the values of the stakeholders, calculations must be done to evaluate each alternative. The score of an alternative in an objective is sent through the appropriate
value function and then weighted appropriately. The equation is shown in \(2.3\)

\[
A1 = \sum_{i=1}^{n} W_i V_i(x_{A1_i})
\]

where \(A1\) is the score for alternative 1, \(W_i\) is the weight of the \(i^{th}\) objective, \(V_i\) is the \(i^{th}\) value function and \(x_{A1_i}\) is the value that \(A1\) would have in the \(n^{th}\) objective and \(n\) is the number of objectives in the decision.

This process is repeated from the bottom to the top of the hierarchy, carrying values from each sub-objective up. Example calculations for Job A, Job B and a middle ground option Job C are shown below and are based off the values shown in table 5.

\[
Job A = 0.43(0) + 0.10(100) + 0.47(70) = 42.9
\]

To quickly dissect how Job A gets a value of 42.9, the decision gets values from each objective which are summed together. The 0.43 is coming from the weight given to the Salary objective. It is multiplied by 0 because on the value function shown in figure 9, the salary of 50k has a value of zero. This method continues for the next
Fig. 10.: Value Function: Commute Time

![Commute Time Value Function](image)

The objectives of Commute and Contributions.

\[
\text{Job } B = 0.43(100) + 0.10(0) + 0.47(30) = 57.1 \quad (2.5)
\]

\[
\text{Job } C = 0.43(75) + 0.10(60) + 0.47(50) = 61.75 \quad (2.6)
\]

Table 5.: Example Job Values

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Salary</th>
<th>Commute</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job A</td>
<td>$50k</td>
<td>0hrs</td>
<td>7</td>
</tr>
<tr>
<td>Job B</td>
<td>$80k</td>
<td>1 Hrs</td>
<td>3</td>
</tr>
<tr>
<td>Job C</td>
<td>$60k</td>
<td>0.5 hrs</td>
<td>5</td>
</tr>
</tbody>
</table>

As can be seen, Job C is the best alternative for our example decision of choosing a Job. From here a decision analyst can look at the value functions and weights and figure out why the model came to the results that it did. In this case, it seems that performing well Job A was out of the running due to the poor performance on the
Fig. 11.: Value Function: Meaningful Contribution

Salary objective. Job C benefits from the shape of the value function for salary. Even though it has a relatively low score, the value function increases rapidly in the lower values. Even with a low score, when the value function is applied to that low score, it has a relatively high value.
CHAPTER 3

METHODOLOGY

Fig. 12.: Methodology Flow Chart
This project will use decision analysis to solve the problem of choosing an optimum nuclear fuel cycle for the United States taking into account the quasi rational perceptions of the General Public. The methodology outlined in §2 is adhered to and shown in figure 12. Reference [1] documents the work performed by John Swanson completing the first portion of the methodology. This thesis documents the work of the author continuing and building on top of John Swanson’s contribution.

3.1 Selection of Stakeholders

Any decision is made by a decision maker. In our case this decision maker is a set of stakeholders in our decision. The first step was to select the appropriate stakeholders. Reference [1] documents the two surveys that were conducted to determine who the General Public considers as the most knowledgeable and relevant subject matter expert/stakeholder in the decision of what nuclear fuel cycle should be used in the United States. The result of this evaluation determined the five subject matter experts to be considered in the study as well as their relative importance. These results are shown in table 6.

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Scientists and Engineers</td>
<td>0.37</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>0.37</td>
</tr>
<tr>
<td>Economists</td>
<td>0.10</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>0.09</td>
</tr>
<tr>
<td>The General Public</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The final score of any fuel cycle alternative will be a combination of the opinions
of each group of subject matter experts weighted according to the above relative importance as shown in equation 3.1

\[ A_i = \sum_j W_j(V value_{ij}) \]  

(3.1)

where \( A_i \) is the score for the \( i^{th} \) fuel cycle alternative, \( W_j \) is the weight for the \( j^{th} \) subject matter expert group and \( Value_{ij} \) is the overall score for the \( i^{th} \) alternative from the \( j^{th} \) subject matter expert. This means the weights and values of each set of stakeholders must be collected to adequately inform the model.

### 3.2 Fuel Cycle Alternatives

This study considers, a list of 10 possible fuel cycle alternatives are being considered. These fuel cycles were selected from among many different possibilities because they are in line with the U.S.’s current strategy. These fuel cycles were decided upon by John Swanson in his work on the project. The list below is adapted from his work.

1. **On-Site Dry Cask Storage (A1)**

   The general method of on-site dry cask storage is to allow used nuclear fuel to cool for a period of about five years in storage pools and then transfer the used nuclear fuel to a canister that is both cooled by natural circulation of air and properly shielded. The containers are then stored at the reactor sites for an undetermined period of time. Full implementation of this scheme is essentially ongoing and requires no additional action.

2. **Permanent Consolidated Dry Cask Storage (A2)**

   This case follows On-Site Dry Cask Storage with the use of dry casks;
however, these dry casks are then transported away from the reactor sites to a centralized national facility where they are stored permanently above ground. Full implementation of this scheme involves having legislation in place that allows this method to proceed, constructing a central facility where the used nuclear fuel can be brought, some implementation of long term security, and developing a transportation network with which to collect the dry casks of used nuclear fuel.

3. Interim Consolidated Storage then Permanent Geological Repository: Closed (A3)

In this case, newly discharged spend fuel is cooled in storage pools for a period of time, about five years, and then transported to a national interim facility where it is consolidated above ground. Additionally, existing dry casks are also transported to the national interim facility and consolidated. After being consolidated, the fuel is then sent to a national permanent geological repository. Once the national permanent geological repository has reached its limit on the amount of used nuclear fuel it can accept, the facility is closed and backfilled to permanently seal the used nuclear fuel away from the biosphere. Full implementation of this scheme involves having legislation in place, constructing both the intermediate facility and the permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

4. Interim Consolidated Storage then Permanent Geological Repository: Retrievable (A4)
This case is a variation Alternative 3 but instead of closing and backfilling the facility when it has reached its limit on the used nuclear fuel it can accept, the facility is maintained and guarded continuously. This allows for the option of retrieving the used nuclear fuel if new technology, economics, or politics permits the utilization of such. Full implementation of this scheme involves having legislation in place that allows this method to be done legally, constructing both the intermediate facility and permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

5. Direct Permanent Geological Repository: Closed (A5)

Newly discharged nuclear fuel is cooled in storage pools for a period of time, after which it is transported directly to a national permanent geological repository. Additionally, existing dry casks are also transported directly to the national permanent geological repository. After the national permanent geological repository has reached its limit on the amount of used nuclear fuel it can accept, the facility is closed and backfilled to permanently seal the used nuclear fuel away from the biosphere. Full implementation of this nuclear fuel cycle involves constructing a permanent repository and constructing a transportation network with which to collect the used nuclear fuel.

6. Direct Permanent Geological Repository: Retrievable (A6)

This case is a variation of Alternative 5 in which instead of closing and backfilling the facility when it has reached its limit on the used nuclear fuel it can accept, the facility is maintained and guarded continuously. This allows the option of retrieving the used nuclear
fuel if new technology, economics, or politics permits the utilization of such. Full implementation of this nuclear fuel cycle involves constructing a permanent repository, and constructing a transportation network with which to collect the used nuclear fuel.

7. Deep Borehole Disposal (A7)

In this case, boreholes approximately 45 centimeters in diameter and 4 to 5 kilometers deep are drilled into the earth and cased. The bottom 1 to 3 kilometers are filled with used nuclear fuel and the rest is backfilled to permanently seal the used nuclear fuel away from the biosphere. Full implementation of this alternative involves developing deep borehole drilling technology, having legislation in place that allows this method to be implemented, and constructing a transportation network with which to collect the used nuclear fuel.

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign (A8)

In this case, used nuclear fuel is removed from reactors and sent to an existing foreign reprocessing facility, e.g., in France. In this facility, the extracted plutonium is blended with depleted uranium and is reprocessed into mixed-oxide fuel (MOX). Additionally, the reprocessed uranium is re-enriched for use as standard uranium oxide fuel. The fuel is then returned to the United States where it is re-utilized in existing light water reactors (LWRs). The high-level waste is also returned to the United States and is disposed of using one of the once-through methods such as a permanent repository. Full implementation of this method involves developing an agree-
ment with a country for the reprocessing of U.S. owned used nuclear fuel, having legislation in place that allows this method to be implemented, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository for the disposal of high-level waste.

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic (A9)

This case is a variant of Alternative 8. In this case, instead of sending the used nuclear fuel to an existing foreign reprocessing facility, a reprocessing facility is constructed in the United States and the used nuclear fuel is transported directly to that location. Full implementation of this scheme involves constructing a used nuclear fuel reprocessing facility, having legislation in places that allows this method to be implemented, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository (or some other once through method) for the disposal of high-level waste.

10. Sodium-cooled Fast Breeder Reactor Implementation (A10)

In this case, there is a large research investment and push into constructing sodium-cooled fast breeder reactors. New nuclear fuel is bred within these new reactors and this fuel, in addition to the used nuclear fuel, is reprocessed and utilized to make electricity both in Light Water Reactors and Sodium Fast Reactors. Full implementation of this nuclear fuel cycle involves having legislation in place that allows implementation, maturing the existing technology to op-
erate commercial sodium-cooled fast breeder reactors, constructing multiple sodium-cooled fast breeder reactors, constructing a transportation network with which to collect and transport the used nuclear fuel, and constructing a permanent repository for the disposal of high-level waste.

3.3 Selection of Objectives and Decision Hierarchy

An objectives hierarchy for the decision model needs to be created based on what objectives one hopes to achieve with the alternatives in section §3.2. This process has been an iterative one. An initial hierarchy is shown in figure 13 and the final hierarchy is shown in figure 14. Further specifics for the initial hierarchy are shown in Appendix A. The difficulty in finding the correct objectives is making it through the clarity test. Many of the initial objectives were fine when it comes to finding direct natural measures but struggled when it came to being fundamental. Take, for example, the objective of “Number of Domestic Uranium Mines” under the “Maximize Fuel Requirement Reduction” under “Maximize Benefits”. While the decision of choosing a nuclear fuel cycle may impact the number of domestic uranium mines, there are many other factors that can impact this such as the availability of natural uranium deposits. In addition, this hierarchy has 62 sub-objectives. The attrition rate when eliciting data to build the model would be too high for our purposes with a hierarchy this large. It is due to these problems for this and other hierarchies, the hierarchy of 14 was decided on. As can be seen, many sub-objectives from the initial hierarchy have been condensed into broader sub-objectives in the final hierarchy.
Fig. 13.: Initial Overall Hierarchy
3.4 Defined Measures and Ranges

3.4.1 Measures

Defining appropriate measures for the objectives is paramount to obtaining accurate values for the ranges they alternatives may take within them. While we have some objectives that have natural measures, like Cost, we have many others that are more difficult to quantify for various reasons. The objectives dealing with radiation exposure have natural measures of Sieverts. The problem with this measure, however, is obtaining reasonable information about each alternative. It is better to use a relative comparison to a common reference value \[21\]. By comparing the exposure that a new fuel cycle may have to the General Public to the current level, experts not only give answers more readily, these answers tend to be more accurate \[21\]. The measures used for each objective is shown in Table 7.

3.4.2 Ranges

Remembering \[2.2\] we need to have a well defined ranges that each alternative may take on each objective. It is only then that we may obtain what can be considered
Table 7.: Measures of Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium Reduction</td>
<td>Percent Reprocessed</td>
</tr>
<tr>
<td>Acceptable Fuel Sizes</td>
<td>Percent of Sizes Accepted</td>
</tr>
<tr>
<td>Acceptable Fuel Types</td>
<td>Percent of Types Accepted</td>
</tr>
<tr>
<td>Short Term Costs (10 years)</td>
<td>Billions of Dollars</td>
</tr>
<tr>
<td>Mid Term Costs (30 years)</td>
<td>Billions of Dollars</td>
</tr>
<tr>
<td>Long Term Costs (100 years)</td>
<td>Billions of Dollars</td>
</tr>
<tr>
<td>Implementation Time</td>
<td>Years</td>
</tr>
<tr>
<td>Odds of Implementation Delays</td>
<td>Percent Chance of Delays</td>
</tr>
<tr>
<td>Odds of a Level 6/7 Accident</td>
<td>Percent Chance of Accident</td>
</tr>
<tr>
<td>Odds of a Level 4/5 Accident</td>
<td>Percent Chance of Accident</td>
</tr>
<tr>
<td>Odds of Theft of Material</td>
<td>Percent Chance of Theft</td>
</tr>
<tr>
<td>Radiation Exposure to Workers</td>
<td>Percent of Current Value</td>
</tr>
<tr>
<td>Radiation Exposure to the General Public</td>
<td>Percent of Current Value</td>
</tr>
</tbody>
</table>
valid objective weights when we attempt to assess the values of the stakeholders.

To define these ranges, experts in nuclear energy were asked to give their opinions on how each alternative may perform on each objective. Understanding that there is much uncertainty in these answers, the experts were to give a minimum, most likely, and maximum value for each measurable objective. This allows us to obtain a triangular probability distribution to use later with our Monte-Carlo analysis.

To be sure that we were clear in what we were asking the experts and that they were understanding of the alternatives, a brief presentation was given along with what requirements there may be for each alternative. These requirements are listed in the explanation of the alternatives in §3.2. An example question is shown in figure 15. The questions were structured so that all 10 fuel cycles were evaluated on one metric at the same time. This allowed the experts to easily rank the alternatives first and then proceed to give values. Five separate groups of nuclear experts participated and the mean of their responses were taken. The results are shown in tables 8, 9, 10, 11 with the results ordered as minimum, most likely, maximum.

Fig. 15.: Expert Alternative Evaluation Example
Table 8.: Expert Alternative Scores: Benefits

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Objectives</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>0,2,4</td>
<td>77,98.4,100</td>
<td>76.6,95.98</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>0,2,4</td>
<td>77,97.4,100</td>
<td>72.6,94.98</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>0,2,4</td>
<td>74.4,94,97.4</td>
<td>66,89.6</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>1.4,9,13</td>
<td>74,93.5,97.4</td>
<td>66,89.4,96</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>2,5,7</td>
<td>74,93.5,97.4</td>
<td>66,89.4,96</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>1.4,9,13</td>
<td>73.6,93.4,97</td>
<td>66,89,96</td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>0,4,8</td>
<td>64.6,87.6,91</td>
<td>62.4,85.6,89.4</td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>15,34,46</td>
<td>54,72.6,87</td>
<td>40,61.6,79.6</td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>14.4,34,46</td>
<td>55,73,88</td>
<td>46,68,86</td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>38,69,87.2</td>
<td>57,75.8,88</td>
<td>50,73,88.8</td>
<td></td>
</tr>
</tbody>
</table>
Table 9.: Expert Alternative Scores: Costs

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1</td>
</tr>
<tr>
<td>A1</td>
<td>5.6,9.4,11.9</td>
</tr>
<tr>
<td>A2</td>
<td>14.4,18.1,21.9</td>
</tr>
<tr>
<td>A3</td>
<td>19.4,25.6,31.9</td>
</tr>
<tr>
<td>A4</td>
<td>21.3,28.8,35</td>
</tr>
<tr>
<td>A5</td>
<td>17.5,21.3,27</td>
</tr>
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<td>A6</td>
<td>19.4,24.4,30.1</td>
</tr>
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<td>A7</td>
<td>16.9,24.4,34.3</td>
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</tr>
<tr>
<td>A9</td>
<td>28.1,34.4,43.8</td>
</tr>
<tr>
<td>A10</td>
<td>28.1,38.1,53.1</td>
</tr>
</tbody>
</table>
Table 10: Expert Alternative Scores: Implementation Liabilities

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I1</td>
</tr>
<tr>
<td>A1</td>
<td>2,9,11</td>
</tr>
<tr>
<td>A2</td>
<td>11,26,44</td>
</tr>
<tr>
<td>A3</td>
<td>10,25.5,40</td>
</tr>
<tr>
<td>A4</td>
<td>15,28.4,43.5</td>
</tr>
<tr>
<td>A5</td>
<td>11,26,2,47</td>
</tr>
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<td>A6</td>
<td>15,27.6,48</td>
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<td>A7</td>
<td>14.5,32,44</td>
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<tr>
<td>A8</td>
<td>9,24,37</td>
</tr>
<tr>
<td>A9</td>
<td>17,31,43</td>
</tr>
<tr>
<td>A10</td>
<td>23,34,49.25</td>
</tr>
</tbody>
</table>
Table 11.: Expert Alternative Scores: Physical Liabilities

<table>
<thead>
<tr>
<th>Alternative</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0,4.5,10</td>
<td>2,10.1,16.4</td>
<td>0.2.4.5.1</td>
<td>-2.3,8</td>
<td>-6,0.6</td>
</tr>
<tr>
<td>A2</td>
<td>0,3.5,8</td>
<td>2,9.3,15.4</td>
<td>0.3.9.8.6</td>
<td>3,11.19.6</td>
<td>-8,-2.4.4</td>
</tr>
<tr>
<td>A3</td>
<td>2.4,6.7,11.2</td>
<td>5.8,12.7,18.4</td>
<td>0.3.9.8.6</td>
<td>3,11.19.6</td>
<td>-6,0.5.4</td>
</tr>
<tr>
<td>A4</td>
<td>3.4,8.1,12.8</td>
<td>6.8,14.1,19.4</td>
<td>0.2.3.9.9.2</td>
<td>4,12.6.21</td>
<td>-5.0.6.4</td>
</tr>
<tr>
<td>A5</td>
<td>1.6,5.1,10.4</td>
<td>3.8,10.1,18</td>
<td>0.6.3.9.9.6</td>
<td>3,10.21</td>
<td>-6,0.5.4</td>
</tr>
<tr>
<td>A6</td>
<td>2.8,5.9,10.6</td>
<td>4.13.1.19</td>
<td>0.2.3.9.8.1</td>
<td>4,11.21</td>
<td>-6,0.7</td>
</tr>
<tr>
<td>A7</td>
<td>1.4,5.7,10.4</td>
<td>3.8,9.16</td>
<td>0.2.3,6</td>
<td>3,10.20</td>
<td>-8,-2.4.4</td>
</tr>
<tr>
<td>A8</td>
<td>4.9,8,18</td>
<td>7,17,26</td>
<td>3,11,19.4</td>
<td>5,18.32</td>
<td>-2,4.11</td>
</tr>
<tr>
<td>A9</td>
<td>1.4,6.8,13.6</td>
<td>2,11.8,20.8</td>
<td>3,11,18.5</td>
<td>5,20.36</td>
<td>-2,3.8.6</td>
</tr>
<tr>
<td>A10</td>
<td>4.4,12.4,28.2</td>
<td>6,21,37.5</td>
<td>3,10.8,18.5</td>
<td>13,28.43</td>
<td>-2,6.16</td>
</tr>
</tbody>
</table>

3.5 Elicitation of Swing Weights and Value Functions

Two different approaches were taken to obtain swing weights and value functions for the decision model. One approach was take for the General Public and another was take for the remaining four stakeholders which are referred to as “experts” below. Both will be outlined below.

3.5.1 Experts

In order to obtain swing weights from experts, direct elicitation was used. While we attempted to gain more than one opinion from each field of expert, due to various reasons, we have only one response per expert area. These responses were collected either face to face or over the phone using the sheet shown in Appendix [C]. The sheet
was used primarily to keep the decision analyst on track and was not filled out by the expert. A copy of the final decision hierarchy was given to the expert to clarify some of the questions asked. This was especially helpful when asking the swing weight questions for the general objectives (Maximize Benefits, Minimize Physical Liabilities, Minimize Implementation Liabilities, and Minimize Costs) because trying to keep all the objectives in a given tree in your head is very difficult. Another difficulty has been trying to have the expert’s assume that when weighting two sub-objectives, that all other objectives are equal. It is a very natural thing to consider “why” some objective might be better or worse. An example would be when considering the objectives of “Time Required for Implementation” vs “Probability for Delays” under the branch of “Implementation Liabilities”. People equate more time required for implementation with higher costs. In order to properly obtain weights, one must separate the cost objective from the time objective, which is unnatural for most.

The SDVFs were evaluated as outlined in §2.3. The value functions were divided into thirds with the appropriate end with the most value given a score of 10 and the end with the least value given a score of 0. The expert was then asked which third of the graph mattered more to them and a weight relative to the 10 and 0 points was assigned to that portion. Again, the survey tool shown in Appendix C was used.

3.5.2 General Public

Eliciting the swing weights and SDVF’s of the General Public required a different approach. It was unfeasible to use a one on one elicitation with the number of people needed due to the statistic demographic from the General Public due to time and financial constraints. Unlike the simple AHP survey questions, the MAVT style survey questions are less intuitive and could be much more difficult to answer, especially for subjects unfamiliar with the MAVT methodology or those that have limited knowledge
of the nuclear fuel cycle. The first attempt at a solution was to create a website. This website would have some baseline information for the respondents and then questions linked through an online survey website. The example questions are shown in figures 16 and 17. The website can be found at [http://nuclearfuelcycle.wixsite.com/nuclearfuelcycle](http://nuclearfuelcycle.wixsite.com/nuclearfuelcycle). We encountered two problems with this approach: not enough traffic to the website and the questions were still not very user friendly. The attrition rate for the survey respondents would be very high, and often the data indicated that the subject had not actually given much though to the questions.

Our next approach solicit the assistance from experts in market research and survey design; Good Run Research & Recreation (GRRR). GRRR was established in 2010 and its experts have over 40 years of consumer research experience. GRRR was able to distill the complicated MAVT style questions into a more consumer friendly questionnaire without losing the aims of the questions. In order to do this, there were small deviations from the methodology outlined in §2.3. For the swing weights, respondents were asked to assign points to different scenarios. These scenarios had one of the objectives being considered at its best value and the rest at their worst. For the SDVF, the sections of the graph are already broken down for the respondents and the respondents are asked to rank that point relative to a 10 and a 1. In addition to being easier to answer, the respondents are given a bit of information to further inform their decisions. To be sure the survey tool was well put together from a consumer standpoint, two focus groups were held. One group had respondents come into the same room an complete the packet over the course of three hours. The second group worked on their own in their homes as the actual respondents would when they received the survey and were interviewed on the phone for feedback on their experience. With the feedback from these groups, the packet shown in Appendix D was created and sent to the General Public. As can be seen, the methodology of
choosing an objective as the most important and awarding points to the remaining objectives as is done with MAVT is intact but the format in which the respondent is given these questions is much simpler. The respondents were given 1 month to return the packet and 154 packets were received.

Fig. 16.: Initial (Website) MAVT Swing Weight Question

Fig. 17.: Initial (Website) MAVT SDVF Question

3.5.3 Discussion on Value Functions

There are two types of value functions, continuous and discrete. Every objective that we are evaluating is continuous over the range we are considering. As such, we need to elicit continuous functions from every stakeholder. As it is impossible to ask
each stakeholder for the value of every possible point, the function is broken into sections and the stakeholders give a few points. To get values for the points that were not directly elicited from the stakeholders, linear interpolation is used. Using linear interpolation may result in slight over or underestimation of the actual value function due to over-fitting. This should not affect the decisions made by the models. The elicited value functions are shown in Appendix E.

It is of utmost importance that our model is additive; that is, all the objectives add value and do not take away. No alternative can have a negative value. This means that fuel cycle alternatives with high monetary costs do not take value away from that alternative, but only add a small amount of value under the cost objective.

3.6 Calculations

Calculating the overall value scores for each alternative is done with respect to the final hierarchy shown in figure 14. As described in §2.4, one starts at the bottom of the hierarchy and works their way up while carrying the score with them. The calculation for each branch of the hierarchy is described below.

3.6.0.1 Cost

Cost is divided into three sub-objectives separated based on time: costs after 10yrs, 30yrs, and 100yrs. These time frames are meant to reflect the costs of implementation, operation, and decommissioning/unforeseen costs. Further discussion on the Cost objectives can be found in [1]. Each stakeholder is asked to weight each cost objective against the others as shown in figure 18. These weights are then multiplied by the value score for the objective in question and these are then summed together for the broader cost objective. This process is shown in equation 3.2.
Fig. 18.: Cost Hierarchy

\[
Cost = w_{C1}V_{C1} + w_{C2}V_{C2} + w_{C3}V_{C3} \tag{3.2}
\]

Where \( w \) is the weight assigned to the cost objective being assessed, \( V \) is the value of the score the alternative being evaluated received based on the stakeholder’s value function with respect to the objective being assessed, \( C1, C2, \) and \( C3 \) are the short term, mid term, and long term cost objectives respectively.

### 3.6.0.2 Maximizing Benefits

Benefits are divided into two sub-objectives: reduction of fuel need (\( B1 \)) and disposal flexibility (\( B.2.3 \)). Within disposal flexibility we are concerned with two things, fuel sizes (\( B2 \)) and fuel types (\( B3 \)) that can be disposed of. Further discussion on the Benefits objectives can be found in [1]. A weight is obtained for fuel sizes and types against one another. Then a weight for reduction of fuel need and disposal flexibility are obtained. The value functions and weights are summed together similar to how the cost objective was done above. The process for benefits is shown in equation 3.3. The benefits hierarchy is shown in figure 19.

\[
Benefits = w_{B1}V_{B1} + w_{B.2.3}(w_{B2}V_{B2} + w_{B3}V_{B3}) \tag{3.3}
\]

Where \( w \) is the weight assigned to the benefits objective being assessed, \( V \) is the
value of the score the alternative being evaluated received based on the stakeholder’s value function with respect to the objective being assessed. B.2.3 the weight assigned to the category of disposal flexibility that is made up of fuel sizes and fuel types applicable to the fuel cycle in question.

3.6.0.3 Minimizing Physical Liabilities

Physical liabilities are divided into three sub-objectives: accidents \((P.1.2)\), theft \((P3)\) of material, and radiation exposure \((P.4.5)\). Accidents is broken up based on magnitude: level 4/5 \((P2)\) and level 6/7 \((P1)\) accidents. Radiation Exposure is broken up based on who is being exposed, workers \((P4)\) or the public \((P5)\). Further discussion on the Physical Liabilities objectives can be found in [1]. The Physical liabilities calculation is similar to the benefits calculation and is shown in equation 3.4. The physical liabilities hierarchy is shown in 20.

\[
Physical = w_{P.1.2}(w_{P1}V_{P1} + w_{P2}V_{P2}) + w_{P3}V_{P3} + w_{P.4.5}(w_{P4}V_{P4} + w_{P5}V_{P5}) \quad (3.4)
\]
Where $w$ is the weight assigned to the physical liability objective being assessed, $V$ is the value of the score the alternative being evaluated received based on the stakeholder's value function with respect to the objective being assessed. As in the Benefits calculations, $P.1.2$ and $P.4.5$ are categories made up of more than one objective.

3.6.0.4 Minimizing Implementation Liabilities

Implementation liabilities are divided into two sub-objectives: time for implementation ($I_1$) and probability for delays ($I_2$). Further discussion on the Implementation Liabilities objectives can be found in [1][1]. The same process is followed here as before and the equation for implementation liabilities is shown in equation (3.5). The implementation liabilities hierarchy is shown in figure [2][1]

$$Implementation = w_{I1}V_{I1} + w_{I2}V_{I2}$$  \hspace{1cm} (3.5)

Where $w$ is the weight assigned to the implementation objective being assessed, $V$ is the value of the score the alternative being evaluated received based on the
stakeholder’s value function with respect to the objective being assessed.

### 3.6.0.5 Global

With the above calculations complete, the weights used for the global objectives of costs ($C$), benefits ($B$), physical liabilities ($P$), and implementation liabilities ($I$) are multiplied by the scores from the above calculations calculated above. These are then added together to get a score for the alternative being assessed. The equation is shown in equation (3.6). Calculations will be carried out for each stakeholder and then be put together using equation (3.1). The global hierarchy is shown in figure 22.

$$V_{A1} = w_B Benefits + w_C Cost + w_P Physical + w_I Implementation \quad (3.6)$$
Where \( w \) is the weight assigned to the objective in question, \( Benefits \) is the value of the benefits tree as calculated in \([3.3]\), \( Cost \) is the value of the cost tree as calculated in \([3.2]\), \( Physical \) is the value of the physical liabilities tree as calculated in \([3.4]\) and \( Implementation \) is the value of the implementation tree as calculated in \([3.5]\). In an attempt to better illustrate these calculations, a graphic of the hierarchy is shown in figure \([23]\) showing the calculations associated with each part of the tree. Note that the value functions are applied only to the 13 measurable objectives. These are then weighted at each level and summed as one moves up the hierarchy.
3.7 Sensitivity Analysis

Sensitivity analysis of the decision model has been done using Monte-Carlo analysis. Monte-Carlo analysis acknowledges the fact that the performance of the alternatives on the 13 metrics is subject to much uncertainty. The Monte-Carlo Analysis runs the model thousands of times while choosing new values for the weights and value functions from within their probabilistic distributions for every run. This allows us to see which decision is truly best within the variability of the alternatives’ performance on the 13 metrics. We are using triangular probability distributions from the expert evaluations of each alternative. The results for each model is the average of 10,000 runs of that model. To run all these simulations, a small script was written in Python. This script is included in Appendix G.

This script takes advantage of a package called “Numpy” which has a function that chooses a number at random from a distribution. There is a triangular distribution function inside Numpy that takes three arguments: Min, Mode, and Max. The Min, Mode and Max were taken from the average of the expert’s judgment on the ten fuel cycle alternatives. An example distribution is shown in figure 24. All the distributions are shown in Appendix F.
Fig. 24.: Sample Distribution Histogram: 1000 samples, 200 bins
CHAPTER 4

RESULTS AND ANALYSIS

The decision models discussed below are based off of 154 responses from the General Public and only one expert for each of the other 4 stakeholder categories. Demographically, these 154 respondents were selected to represent the demographics of the voting public in the United States. The demographics of our sample are shown in table 12. A model will be shown for all stakeholders individually as well as a combined weighted model according to the stakeholder analysis in §3.1. It must be kept in mind that the results for the experts are based off too small a sample to be considered statistically significant. Each model was run 10,000 times using the Monte-Carlo simulations mentioned described in §3.7.
Table 12.: Demographics of General Public Survey

<table>
<thead>
<tr>
<th>Gender</th>
<th>Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>High School or GED 16%</td>
</tr>
<tr>
<td>Female</td>
<td>Associate’s 14%</td>
</tr>
<tr>
<td></td>
<td>Bachelor’s 45%</td>
</tr>
<tr>
<td>Age</td>
<td>Master’s 24%</td>
</tr>
<tr>
<td>18-34</td>
<td>PHD 2%</td>
</tr>
<tr>
<td>35-44</td>
<td>26%</td>
</tr>
<tr>
<td>45-64</td>
<td>8%</td>
</tr>
<tr>
<td>65+</td>
<td>East 31%</td>
</tr>
<tr>
<td>Ethnicity</td>
<td>Midwest 24%</td>
</tr>
<tr>
<td>African American 21%</td>
<td>South 25%</td>
</tr>
<tr>
<td>Asian</td>
<td>West 20%</td>
</tr>
<tr>
<td>Caucasian</td>
<td>54%</td>
</tr>
<tr>
<td>Hispanic</td>
<td>13%</td>
</tr>
<tr>
<td>Other</td>
<td>&lt;30K 10%</td>
</tr>
<tr>
<td></td>
<td>30-49K 14%</td>
</tr>
<tr>
<td></td>
<td>50-74K 22%</td>
</tr>
<tr>
<td>Marital Status</td>
<td>50-74K 22%</td>
</tr>
<tr>
<td>Never Married</td>
<td>32% 74-99K 20%</td>
</tr>
<tr>
<td>Married</td>
<td>51%</td>
</tr>
<tr>
<td>Divorced</td>
<td>14% 150K+ 16%</td>
</tr>
<tr>
<td>Widowed</td>
<td>2%</td>
</tr>
</tbody>
</table>

4.1 General Public

The General Public’s decision model gave results shown in table 13. Rather than look at the General Public’s overall answer, it may be more informative to look at why the General Public chose what they did.
<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.567</td>
</tr>
<tr>
<td>A2</td>
<td>0.521</td>
</tr>
<tr>
<td>A5</td>
<td>0.474</td>
</tr>
<tr>
<td>A8</td>
<td>0.472</td>
</tr>
<tr>
<td>A9</td>
<td>0.469</td>
</tr>
<tr>
<td>A6</td>
<td>0.464</td>
</tr>
<tr>
<td>A7</td>
<td>0.452</td>
</tr>
<tr>
<td>A3</td>
<td>0.449</td>
</tr>
<tr>
<td>A4</td>
<td>0.445</td>
</tr>
<tr>
<td>A10</td>
<td>0.437</td>
</tr>
</tbody>
</table>

These results are based on weights on each individual objective shown in figure 23. These weights are calculated by multiplying down each branch of the hierarchy shown in 23 to see how much each individual measured objective impacts the model. As can be seen, the General Public feels that the reduction of uranium mined is very important. This is good for the fuel cycle alternatives that involve some form of reprocessing. It seems, however, that the sum of several “less important” objectives resulted in a more dominant objective than the “very important” objective of minimizing mining.
Figure 26 shows how each broad objective contributes to the value of each of the various fuel cycle alternatives. This illustrates that, according to the General Public, the category of Physical Implementations does not help too much in choosing among the fuel cycles. Most of the differences seem to come from the Benefits objective and the Cost objective.

In order to interpret these results, it is important to remember that the value associated to all the objectives is always positive. For fuel cycle alternatives in which a given objective does not perform well, its value added will be small. Looking at A1,
the Cost objective adds a significant amount of value to the alternative while there isn’t much in the way of Benefits while A10 is just the opposite. A10 has a large contribution to value from the Benefits where as Cost doesn’t add much. Another large value for A1 comes from the objective of Implementation Liabilities. As A1 is the current method of used nuclear fuel disposal (essentially, the “do nothing” alternative”, it has a very short implementation time and there is a very small chance of delays.

Fig. 26.: General Public: Stacked Bar Graph

Figure 28 provides another way to look at the General Public’s decision. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that cost in this sense is not the Cost objective but is all the “negative” objectives being summed together. Again, it must be noted that value is always positive. The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. Figure 27 has been included to further help understand the interpretation of figure 28.
As can be seen in figure 28, there are some alternatives that are dominated by others. For example, A2 will always dominate A7 because it scores better on “cost” items than A7 and the same on the benefit items according to the General Public’s model. A rational decision maker would never choose A7 which has worst “cost” value and the same benefit value as A2. The author’s interpretation of figure 28 leaves only alternatives A1, A5, A6, A8, and A9 for consideration.
Further insight into why the General Public chose A1 can be gleaned from figure 29. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as figure 26 but it also allows one to look at how far from ideal the solution is. As can be seen in figure 26, A1 performs almost perfectly in costs but leaves much to be desired in terms of benefits. A10 performs almost in the exact opposite way of A1. There is a significant value in benefits but almost no value in costs and implementation.
Fig. 29.: General Public: Value Gaps
4.2 Economists

The Economists decision model gave results shown in table 14. As with the case of the General Public, looking at how the Economists decision came about is much more informative of how the fuel cycle alternatives look to Economists. As stated before, only 1 Economist gave their values so results must be considered with that in mind.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.636</td>
</tr>
<tr>
<td>A2</td>
<td>0.620</td>
</tr>
<tr>
<td>A5</td>
<td>0.550</td>
</tr>
<tr>
<td>A6</td>
<td>0.539</td>
</tr>
<tr>
<td>A3</td>
<td>0.539</td>
</tr>
<tr>
<td>A4</td>
<td>0.522</td>
</tr>
<tr>
<td>A7</td>
<td>0.515</td>
</tr>
<tr>
<td>A8</td>
<td>0.471</td>
</tr>
<tr>
<td>A9</td>
<td>0.451</td>
</tr>
<tr>
<td>A10</td>
<td>0.393</td>
</tr>
</tbody>
</table>

Figure 30 shows the global weights for the Economist for each measurable objective. The Economist is not concerned with the exposure to workers. During the elicitation process, he made sure to justify this by mentioning he feels they should be compensated for any exposure they encounter.
Figure 31 shows how each broad objective contributes to the value of each fuel cycle alternative. This shows that, according to the Economist, most of the fuel cycles perform well on the cost objective. During the elicitation process, the Economist mentioned that being a macro-economist, all of the proposed costs are “drops in the bucket” as far as he is concerned. As before, a significant bump in value comes from the Implementation objective for A1.
Figure 32 provides another way to look at the Economist’s decision. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that cost in this sense is not the Cost objective but is all the “negative” objectives being summed together. The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. As shown here, A1 dominates most other alternatives in the eyes of the Economist.
Further insight into the decision made by the Economist can be gleaned from figure 33. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as figure 31 but it also allows one to look at how far from ideal the solution is. As can be seen in figure 31, most alternatives do very well in the cost objective except for A10. Again, this is because the economist sees these costs as relatively insignificant to everything else. This can be confusing because the weights associated to cost do not reflect this but the values obtained by the objectives do. When eliciting the value functions and swing weights from the Economist, the author pressed him on this inconsistency. He felt that the cost is something that is very important for the implementation of a fuel cycle but these objectives, in his mind, performed well
on the proposed ranges.

Fig. 33.: Economist: Value Gaps
4.3 Environmental Scientists

The Environmental Scientists decision model gave results shown in Table 15. As before, looking at how the Environmental Scientists decision came about is much more informative of how the fuel cycle alternatives look to Environmental Scientists. As stated before, only 1 Environmental Scientist gave their values so results must be considered with that in mind.

Table 15.: Environmental Scientists: Results

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.418</td>
</tr>
<tr>
<td>A10</td>
<td>0.381</td>
</tr>
<tr>
<td>A8</td>
<td>0.380</td>
</tr>
<tr>
<td>A2</td>
<td>0.370</td>
</tr>
<tr>
<td>A9</td>
<td>0.355</td>
</tr>
<tr>
<td>A5</td>
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<td>A6</td>
<td>0.260</td>
</tr>
<tr>
<td>A7</td>
<td>0.250</td>
</tr>
<tr>
<td>A3</td>
<td>0.248</td>
</tr>
<tr>
<td>A4</td>
<td>0.246</td>
</tr>
</tbody>
</table>

Figure 34 shows the global weights for the Environmental Scientist for each measurable objective. There are a few objectives that were given zero weight. This is because during the elicitation, when asked to compare that objective to the objectives that were already ranked, they chose to give that objective or branch of objectives a zero indicating it doesn’t matter at all to them. These are the objectives of Fuel Sizes, Fuel Types, and Delays.
Figure 35 shows how each broad objective contributes to the value of each fuel cycle alternative. This graph shows the most influential objectives are Benefits and Implementation. While this can be seen in figure 34, this shows how that can keep an alternative in the running or eliminate one. A1 and A10 both did well but for vastly different reasons. A1 is a quick fix which is valuable to the Environmental Scientist but is extremely lacking in Benefits. A10 on the other hand has massively more Benefit but is lacking in the Implementation category.
Figure 36 provides another way to look at the Environmental Scientist’s decision. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that *cost in this sense is not the Cost objective but is all the “negative” objectives being summed together.* The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. According to the Environmental Scientist’s values, A9, A4, A7, and A3 are dominated by other alternatives. This is because they score similarly on Benefits but worse on Cost meaning they would be an illogical choice for a solution. The author’s interpretation of figure ?? leaves only alternatives A1, A8, and A10 for consideration.
Further insight into the decision made by the Environmental Scientist can be gleaned from figure 37. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as 35 but it also allows one to look at how far from ideal the solution is. As can be seen in figure 35 most of the alternatives do very poorly on the Benefits category compared to the Utopian solution until we get the the reprocessing fuel cycles. This is because weights of zero were put on all the Benefit objectives other than the Reduction of New Uranium Mined.
Fig. 37.: Environmental Scientists: Value Gaps
4.4 Nuclear Scientists and Engineers

The Nuclear Scientists and Engineers decision model gave results shown in Table 16. As before, looking at how the Nuclear Scientists and Engineers decision came about is much more informative of how the fuel cycle alternatives look to Nuclear Scientists and Engineers. As stated before, only 1 Nuclear Engineer gave their values so results must be considered with that in mind.

Table 16.: Nuclear Scientists and Engineers: Results

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.605</td>
</tr>
<tr>
<td>A2</td>
<td>0.557</td>
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<td>A5</td>
<td>0.460</td>
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<td>0.436</td>
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<td>A7</td>
<td>0.432</td>
</tr>
<tr>
<td>A9</td>
<td>0.424</td>
</tr>
<tr>
<td>A4</td>
<td>0.407</td>
</tr>
<tr>
<td>A10</td>
<td>0.283</td>
</tr>
</tbody>
</table>

Figure 38 shows the global weights for the Nuclear Engineer for each measurable objective. There are a few objectives that were given zero weight. This is because during the elicitation, when asked to compare that objective to the objectives that were already ranked, they chose to give that objective or branch of objectives a zero indicating it doesn’t matter at all to them. These are the objectives of Level 4/5 accidents, Worker Exposure, and General Public Exposure. The objective that
mattered most was that of Theft.

Figure 38.: Nuclear Scientists and Engineers: Weights

![Nuclear Scientists and Engineers: Global Weights](image)

Figure 39 shows how each broad objective contributes to the value of each fuel cycle alternative. The objectives that vary the most among fuel cycles is that of Cost and Implementation. Because A1 performs very well on these two objectives, it has a very high value compared to the other alternatives.
Figure 40 provides another way to look at the Nuclear Scientist’s decision. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that cost in this sense is not the Cost objective but is all the “negative” objectives being summed together. The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. According to the Nuclear Engineer’s values, $A1$, $A8$, $A9$, and $A10$ dominate all other fuel cycles. The author’s interpretation of figure 28 leaves only alternatives $A1$, $A8$, and $A9$ for consideration.
Further insight into the decision made by the Nuclear Scientist can be gleaned from figure [11]. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as [39] but it also allows one to look at how far from ideal the solution is. As can be seen in figure [39], the objective with the most potential value is that of Physical Liabilities but most of the alternatives score low in this objective. This is due to the very low tolerance set forth by the Nuclear Engineer in his value functions.
Fig. 41.: Nuclear Scientists and Engineers: Value Gaps
4.5 Political Scientists

The Political Scientists decision model gave results shown in table 17. As before, looking at how the Political Scientists decision came about is much more informative of how the fuel cycle alternatives look to Political Scientists. As stated before, only 1 Political Scientist gave their values so results must be considered with that in mind.

Table 17.: Political Scientists: Results

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
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<tr>
<td>A2</td>
<td>0.488</td>
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<td>A7</td>
<td>0.378</td>
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<tr>
<td>A3</td>
<td>0.374</td>
</tr>
<tr>
<td>A6</td>
<td>0.370</td>
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<tr>
<td>A4</td>
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</tr>
<tr>
<td>A8</td>
<td>0.340</td>
</tr>
<tr>
<td>A9</td>
<td>0.332</td>
</tr>
<tr>
<td>A10</td>
<td>0.283</td>
</tr>
</tbody>
</table>

Figure 42 shows the global weights for the Political Scientist for each measurable objective. The objectives of Theft and Implementation are much higher than the rest of the weights where Fuel Sizes, Fuel Types, and Mid Term Costs are the lowest.
Figure 43 shows how each broad objective contributes to the value of each fuel cycle alternative. This shows that the largest contributors to the value of a fuel cycle is the Physical Liabilities objective. While it may have the largest impact on the overall scores of the objectives, they are similar across all the alternatives, so Physical Liabilities does not help make the decision. The objectives that do contribute to the decision are Implementation Liabilities and Cost. These two objectives change significantly among fuel cycle alternatives.
Figure 44 provides another way to look at the Political Scientist’s decision. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that cost in this sense is not the Cost objective but is all the “negative” objectives being summed together. The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. According to the Political Scientist’s values, A1 is dominating all but A10 in this decision space. The Benefits for all but A10 are very similar, so in the Political Scientist’s value system, A1 is a logical decision. It is a cheap, immediate solution that has about the same Benefit value as A2 through A9.
Further insight into the decision made by the Political Scientist can be gleaned from figure 45. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as 43 but it also allows one to look at how far from ideal the solution is. As can be seen in figure 43 and as mentioned before, the Physical Liabilities objective has the most room for improvement on all fuel cycle alternatives but varies little among these alternatives.
Fig. 45.: Political Scientists: Value Gaps
4.6 All Stakeholders

The results for the full model with all all the stakeholders carrying the appropriate amount of weight are shown in table 19. As before, we will be looking at what has driven this decision. For reference, the weight each stakeholder holds in this decision is shown again in table 18 below.

Table 18.: Subject Matter Experts and Weights from [1]

<table>
<thead>
<tr>
<th>Subject Matter Expert</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Scientists and Engineers</td>
<td>0.37</td>
</tr>
<tr>
<td>Environmental Scientists</td>
<td>0.37</td>
</tr>
<tr>
<td>Economists</td>
<td>0.10</td>
</tr>
<tr>
<td>Political Scientists</td>
<td>0.09</td>
</tr>
<tr>
<td>The General Public</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figure 46 shows averaged global weights for all the stakeholders for each measurable objective. The two objectives of largest concern are Uranium Reduction and Theft while the least concern is given to Workers Exposure.
Table 19.: Full Weighted Model: Results

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Score (Maximum score of 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.557</td>
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<tr>
<td>A2</td>
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<td>A3</td>
<td>0.381</td>
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<tr>
<td>A7</td>
<td>0.374</td>
</tr>
<tr>
<td>A4</td>
<td>0.371</td>
</tr>
<tr>
<td>A10</td>
<td>0.363</td>
</tr>
</tbody>
</table>

Figure 46 shows averaged global weights for all the stakeholders for each measurable objective. The two objectives of largest concern are Uranium Reduction and Theft while the least concern is given to Workers Exposure.
Figure 47 shows how each broad objective contributes to the value of each fuel cycle alternative. This shows that the most variable, and thus influential objectives are Benefits, Costs, and Implementation Liabilities. The Physical Liabilities do not change too much, therefore not aiding in differentiating between objectives.
Figure 48 provides another way to look at the decision made by all the stakeholders. This plot shows all of the “cost” objectives and the value that they provide the alternative vs the Benefit objective. It is important to note that cost in this sense is not the Cost objective but is all the “negative” objectives being summed together. The ideal case would be a point in the upper right quadrant while the worst case would be in the lower left. According to the weighted values of our stakeholders, A1, A8, A9, and A10 are dominating the other alternatives.
Further insight into the decision made by the all the stakeholders can be gleaned from figure 49. A value gap is how far from the Utopian solution an alternative is. The top of the bar is the value the Utopian solution would have in the corresponding category, the black bar is how the alternative scored thus the white section of the bar is the value gap. Analyzing the value gap of each alternative gives a similar look at the data as figure 47 but it also allows one to look at how far from ideal the solution is. As can be seen in figure 47, as before, Physical Liabilities has the most room for improvement as it is highly valued by the stakeholders but the alternatives perform poorly on it based on the stakeholders value functions.
Fig. 49.: Full Weighted Model: Value Gaps
4.7 Best Decision and Why

According to the models we have created and the stakeholder’s scale of values and priorities, On Site Dry Cask Storage (A1), i.e. the “do nothing” alternative, is unanimously the best decision. This result occurs whether we consider the value functions as linear or the stakeholder-informed value functions. The author feels that this result is from the methodology governing the structure of the hierarchy. Because the methodology dictates that only the objectives that are directly affected by the decision at hand (i.e., fundamental objectives), many of the benefits associated with the use of nuclear power for electricity production have been somewhat disregarded because they appear to be strategic objectives. Many of the benefits of nuclear power are geared toward strategic objectives. If more of the benefits of nuclear power would have been considered as fundamental objectives, the benefits section of the hierarchy may have received more weight. Take, for example, the objective of reducing the weight of new uranium mined. If, instead, that objective were to reduce the nation’s dependence on foreign uranium or reduce environmental damage, it may appear to the stakeholders as more important. The problem is these objectives are not only affected by the decision of a new fuel cycle, but the new fuel cycle may be a means to achieving that objective.

The author also thinks that the decision hierarchy ranges are skewed from reality due to regulation. The Nuclear Regulatory Commission (NRC) would never allow a fuel cycle to be implemented that has the odds of an accident during its lifetime of 40%. While this is what the experts said the maximum value may be, it would never be approved for implementation. If the ranges given to physical liabilities would have been informed not only by the best guess provided by a few experts, but by the reality check provided by a regulator, the weight given might have been significantly lower.
Another interesting point is that Physical Liabilities is always one of the highest weighted objectives among the stakeholders yet it has the smallest variability when it comes to the values each alternative takes for this objective. This means that while people care a lot about things like exposure, safety, and theft, no matter which alternative is chosen, they get about the same value from it. This means that the objectives under Physical Liabilities *could* be removed from the model and not much change should be expected among the ranking of the fuel cycle alternatives.
5.1 Conclusions

The long term management of used nuclear fuel in the U.S. is an issue not yet resolved. This work considers ten different fuel cycles including once through cycles, reprocessing/recycling fuel cycles and implementation of a fast breeder reactor. In order to assess the impacts of these fuel cycles, five groups of technical experts were surveyed as to how each fuel cycle would perform on each of our thirteen measurable objectives. With these scores in hand, we were able to address two large issues standing in the way of the implementation of these fuel cycles: politics and public perception. In order to overcome these issues, it is beneficial to understand the values and beliefs of the stakeholders involved. We have done this through the framework of decision analysis, specifically MAVT.

We have used the MAVT to assess the values and beliefs of Economists, Environmental Scientists, Nuclear Scientists, Political Scientists and the General Public and apply these to give scores for ten different fuel cycles. This was achieved through the use of swing weights and single dimensional value functions (SDVF). While we followed the typical elicitation with the Expert stakeholders, this does not work with the General Public. In order to match the demographics of the U.S. and create a consumer friendly questionnaire, we partnered with Good Runs Research and Recreation (GRRR) and received 154 respondents. After constructing a model for each stakeholder as well as one that combines the stakeholders values according to how qualified each stakeholder is viewed according to the General Public, the results have
allowed us insight as to why this problem has yet to be solved.

No matter which model is looked at, the top scoring fuel cycle is A1, On-Site Dry Cask Storage. This is the “do nothing” fuel cycle that we are currently using in the United States where used nuclear fuel is left in cooling pools or on site in dry casks. This result reflects that stakeholders have a very high concern with objectives we consider physical liabilities, implementation liabilities and cost while not as much concern with benefits that we have considered. There is also the issue that some values elicited from experts about the fuel cycles would be outside what could be approved by a regulative body. This means that a fuel cycle would never be built that had, say, a 40% chance of a level 6/7 accident happening during its lifetime. This will undoubtedly affect the amount of weight given the the objective of “accidents.”

These results, as stated before, reflect the values of the stakeholders involved. We are able to see that if we want to change the current method of waste disposal, we either need to change the values of the stakeholders to recognize potential benefits and worry less about costs. The other option is we need to choose a fuel cycle that can be implemented quickly, cheaply, and safely, or we may need to look at more than just monetary costs of a fuel cycle. In that sense it may cost more to “do nothing” than we think.

5.2 Future Work

To continue this work, the most important step is to increase the number of elicitations done on Experts for their SDVF’s and their swing weights. To adequately put together the entire decision model, we need more than the one data point that we have thus far for each expert stakeholder. With more time and a larger budget, the author thinks that the survey methodology developed for the General Public would be suitable to elicit the opinion of a statistically significant group of experts.
We also need to look at how variations of the weights within the values given by experts and the General Public will affect the decision. This will allow us to see how stable the decision is as people’s values fluctuate over time. This can be implemented using the python code already in use and varying the inputs for the weights or by using a distribution as used with the expert scores for each alternative. It may also prove valuable to do a “What If” analysis, where we look into what the weights might need to be in order to have a specific alternative be chosen.

To continue this work in the scope of the Nuclear Rebranding Project, it may be beneficial to look deeper into the General Public’s responses. While this portion of the project has looked at bringing the General Public’s quasi-rational opinions to the same decision space as the experts, it has not looked into why the General Public believes what they believe. In addition to this, looking at the General Public’s value gap analysis provides insight to where they feel improvements can be made. This information can help guide the branding strategy and communications plan in part 3 of the project. Looking at responses relative to demographic information may also prove beneficial.
INSTITUTIONAL REVIEW BOARD DISCLAIMER

In order to conduct research that involves human participants, a review from the Institutional Review Board (IRB) may be required. This work is exempt from IRB review according to HHS regulations section 46.101.b.2 which states:

(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, is exempt from IRB review, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects’ responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects’ financial standing, employability, or reputation [22].

This work involves surveys where the information is recorded in such a manner that human subjects cannot be identified and none of the information collected could ever place the subjects at risk of any criminal or civil liability, or damage their reputation in any way.
REFERENCES


Appendix A

INITIAL HIERARCHY
Fig. 50.: Initial Overall Hierarchy

Select the Best Nuclear Fuel Cycle for the U.S.

Maximize Benefits
- Maximize Disposal Flexibility
- Fuel Requirement Reduction
- National Infrastructure Development
- Legal Resolution
- Local Economic Development
- Public & Political Acceptance
- Increase Technical Workforce

Maximize Opportunities
- American Economic Development
- Energy Policy Leadership
- Long-term Energy Production
- New Technology Development
- Nuclear Industry Growth
- U.S. Government Competence

Minimize Costs
- Facility Construction, Operation, & Maintenance
- Legal Fees & Fines
- Licensing
- Proliferation Prevention
- Supplemental Infrastructure Development
- Switching Policy

Minimize Risks
- Accidents or Nuclear Material Release
- Potential Future Burden
- Proliferation Potential
- Public or Political Rejection
- Radiation Exposure
- Supply Availability
- Technical Feasibility
Fig. 51.: Initial Benefits Hierarchy
Fig. 52: Initial Opportunities Hierarchy
Fig. 53.: Initial Costs Hierarchy
Fig. 54.: Initial Risks Hierarchy
Appendix B

EXPERT TECHNICAL ASSESSMENT SURVEY TOOL
B1 – What would be the reduction in required new fuel (by weight) that would be expected after full implementation?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
B1 – What would be the reduction in required new fuel (by weight) that would be expected after full implementation?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
**We are trying to gauge the flexibility of the given fuel cycle and its ability to accept PWR, BWR, SMR, FBR, HTGR, ATF, or any future fuel sizes.**

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed
B2 - What percentage of available fuel sizes would be processed after full implementation?

6. Direct Permanent Geological Repository: Retrievable

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
B3 – What percentage of fuel types would be processed after 30 years?

**We are trying to gauge the flexibility of the given fuel cycle and its ability to accept PWR, BWR, SMR, FBR, HTGR, ATF, or any future fuel sizes.

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed
B3 – What percentage of fuel types would be processed after 30 years?

6. Direct Permanent Geological Repository: Retrievable

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
C1 – What would be the total cost after 10 Years of implementation?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
C1 – What would be the total cost after 10 Years of implementation?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
C2 – What would be the total cost after 30 Years of implementation?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
C2 – What would be the total cost after 30 Years of implementation?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
C3 – What would be the total cost after 100 Years of implementation?

1. On-Site Dry Cask Storage

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

2. Permanent Consolidated Dry Cask Storage

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

5. Direct Permanent Geological Repository: Closed

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B
C3 – What would be the total cost after 100 Years of implementation?

6. Direct Permanent Geological Repository: Retrievable

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

7. Deep Borehole Disposal

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B

10. Sodium-cooled Fast Breeder Reactor Implementation

$225 B $325 B $425 B $525 B $625 B $725 B $825 B $925 B $1025 B $1125 B
C3 – What would be the total cost after 100 Years of implementation?
I1 – What is the time required (in years) for implementation?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
I1 – What is the time required (in years) for implementation?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
I2 – What is the probability of unforeseen delays during implementation?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
I2 – What is the probability of unforeseen delays during implementation?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
P1 – What is the probability of a level 6 or 7 nuclear accident within 100 years?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
P1 – What is the probability of a level 6 or 7 nuclear accident within 100 years?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
P2 – What is the probability of a level 4 or 5 nuclear accident within 100 Years?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
P2 – What is the probability of a level 4 or 5 nuclear accident within 100 Years?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
P3 – What is the probability of a successful nuclear theft within 100 years?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
P3 – What is the probability of a successful nuclear theft within 100 years?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
What would be the change in average radiation exposure to workers at nuclear facilities?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed

6. Direct Permanent Geological Repository: Retrievable
P4 – What would be the change in average radiation exposure to workers at nuclear facilities?

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs:
   Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs:
   Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
P5 – What would be the change in average radiation exposure to the public near nuclear facilities?

1. On-Site Dry Cask Storage

2. Permanent Consolidated Dry Cask Storage

3. Interim Consolidated Storage Then Permanent Geological Repository: Closed

4. Interim Consolidated Storage Then Permanent Geological Repository: Open

5. Direct Permanent Geological Repository: Closed
P5 – What would be the change in average radiation exposure to the public near nuclear facilities?

6. Direct Permanent Geological Repository: Retrievable

7. Deep Borehole Disposal

8. Spent Fuel Reprocessed and Recycled in Existing LWRs: Foreign

9. Spent Fuel Reprocessed and Recycled in Existing LWRs: Domestic

10. Sodium-cooled Fast Breeder Reactor Implementation
Appendix C

EXPERT SWING WEIGHT AND SDVF SURVEY TOOL
Physical Liabilities

Accidents

Choice A
There is a 40% probability that a Level 6 or 7 accident will occur, BUT there is a 0% probability that a Level 4 or 5 accident will happen. _____

Choice B
There is a 40% probability that a Level 4 or 5 accident will occur, BUT there is a 0% probability that a Level 6 or 7 accident will happen. _____

6/7 Rating

<table>
<thead>
<tr>
<th>0%</th>
<th>15%</th>
<th>25%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

4/5 Rating

<table>
<thead>
<tr>
<th>0%</th>
<th>15%</th>
<th>25%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Exposure

Choice A
The amount of radiation exposure for nuclear facility workers is increased by 50%, but the radiation exposure for the general public is decreased by 10%. _____

Choice B
The amount of radiation exposure for the general public is increased by 50%, but the radiation exposure for nuclear facility workers is decreased by 10%. _____

Worker Exposure Rating

<table>
<thead>
<tr>
<th>Decrease by 10%</th>
<th>Decrease by 5%</th>
<th>Increase by 25%</th>
<th>Increase by 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

General Public Exposure Rating

<table>
<thead>
<tr>
<th>Decrease by 10%</th>
<th>Decrease by 5%</th>
<th>Increase by 25%</th>
<th>Increase by 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Theft Rating

<table>
<thead>
<tr>
<th>0%</th>
<th>5%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
Overall
Choice A
The probability that there will be Level 4, 5, 6, or 7 accident is 0%, BUT the radiation exposure for facility workers and the general public is increased by 50%, AND there’s a 20% chance of nuclear theft.

Choice B
Radiation exposure for facility workers and the general public is decreased by 10%, BUT there is a 40% probability of an accident (either Level 4, 5, 6, or 7), AND there’s a 20% chance of nuclear theft.

Choice C
There is no chance (0% probability) of nuclear theft, BUT there is a 40% probability of an accident (either Level 4, 5, 6, or 7), AND radiation exposure increases by 50% for both facility workers and the general public.

Implementation
Time
Choice A
Full implementation of the new fuel cycle will take 50 years, BUT there is no chance (0% probability) for unforeseen delays.

Choice B
Full implementation of the new fuel cycle will be effective immediately, BUT there is a 100% probability for unforeseen delays.

Time Rating
0yrs 10yrs 30yrs 50yrs
10   _____   _____   0

Delay Rating: Odds of a delay
0%  25%  50%  100%
10   _____   _____   0
Cost

Choice A
The nuclear fuel cycle will cost $5 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will be at $160 Billion, and over the long-term (100 years), the total cost will be $600 Billion.

Choice B
The nuclear fuel cycle will cost $40 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will still be at $40 Billion (no additional costs incurred from years 10 to 30), and over the long-term (100 years), the total cost will be $600 Billion.

Choice C
The nuclear fuel cycle will cost $40 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will be at $160 Billion, but over the long-term (100 years), the total cost will be $160 Billion (no additional costs incurred from years 30 to 100).

Short Term Cost Rating
$5B   $15B   $30B   $40B

    10     _____  _____   0

Mid Term Cost Rating
$40B   $80B   $120B  $160B

    10     _____  _____   0

Long Term Cost Rating
$160B  $300B  $450B  $600B

   10     _____  _____   0
Benefits

Flexibility

Choice A
The cycle is 100% flexible to accommodate any types of fuel, BUT disposal containers can only accommodate half (50%) of the sizes / shapes of fuel pellets and rods.

Choice B
The cycle is 100% flexible so that disposal containers can accommodate any sizes/shapes of fuel, BUT the fuel cycle can only handle half (50%) of potential fuel types.

Acceptable Type Rating

<table>
<thead>
<tr>
<th>Rating</th>
<th>50%</th>
<th>70%</th>
<th>80%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>0</td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

Flexibility of shape and size rating

<table>
<thead>
<tr>
<th>Rating</th>
<th>5%</th>
<th>70%</th>
<th>80%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>0</td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

Reduction in Uranium rating

<table>
<thead>
<tr>
<th>Rating</th>
<th>0% (no recycling)</th>
<th>30%</th>
<th>60%</th>
<th>90% (90% is reused/recycled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>0</td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

Overall Benefits

Choice A
The cycle is 100% completely flexible to accommodate any types or sizes or shapes of fuel, BUT the cycle would not reduce the amount of new uranium required at all (0% can be reused/recycled).

Choice B
The cycle reuses or recycles 90% of the spent fuel, BUT the fuel cycle only works with 50% of the current types and sizes/shapes of nuclear fuel which are already in use.

Overall
Please spread 100 points among the following categories. Allot more points to show more importance

Maximizing Benefits

Minimizing Physical Liabilities

Minimizing Implementation Liabilities

Minimizing Costs

Total: 100
Appendix D

GOOD RUNS RESEARCH AND RECREATION SURVEY

This questionnaire was developed to elicit the swing weights and single dimensional value functions from the general public for use in the MAVT model. Traditionally, these weights are elicited in person with a small group of people who are knowledgeable with the subject matter to be discussed. This methodology needed to be adapted to a self guided survey that could be given to people who do not necessarily have knowledge with the nuclear fuel cycle.

This was accomplished through a partnership with Good Runs Research and Recreation. Once the packet was created to inform but not bias respondents, two focus groups were held. One was a three hour session where respondents came into a meeting room and filled out the survey. A discussion was then held to further refine the tool. The second focus group was held remotely. The survey was sent as it would be during the actual administration and results were collected. A follow up conversation via telephone was then had to address and comments or concerns about the survey tool. Adjustments were made from each focus group which led to the final product shown here.
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Let’s get started!

ASSIGNMENT 1

ASSIGNMENT 2

ASSIGNMENT 3

ASSIGNMENT 4
Hello!

We’re going to spend some time understanding the nuclear fuel cycle. Sounds like fun, right? Don’t worry, we’ll take it step by step and we’ll learn together as we go. Your workbook contains four assignments to complete by DATE. You can do them all at once, or you can spread them out over time - your choice! Once you have completed all the assignments and we have received your completed workbook, you will be awarded $.

Throughout the assignments, we’re going to share some information with you to help you learn how nuclear fuel is produced, used, and disposed. And then we want to measure your opinions about different aspects of the process. This will help us to determine which alternative(s) for establishing a nuclear fuel cycle in the United States would best match with what Americans want. It may sound pretty heavy, but it’s certainly an important question facing our country today, and your input is invaluable to us.

One of the ways we’ll be measuring your opinion is through providing scenarios, and you’ll tell us which scenario you prefer. Some of these scenarios won’t seem very realistic, but what we’re trying to do is understand your overall priorities when it comes to things like risk, safety, costs, etc. In some scenarios, it may seem that both choices are bad. In other scenarios, it may seem like the scenarios are both acceptable. Or maybe, in some scenarios, there will be a very clear choice for you personally.

In any case, we’ll want you to pick the one that you prefer, and we’ll want to know by how much you prefer that one. This will help us understand your opinions and priorities. And we’ll finish up each section by measuring how important each of these factors is to you.

Ready to get started? Here we go!
First, let’s start by learning a little about the basics of the nuclear fuel cycle. These six steps (below) illustrate a basic overview of the process: nuclear fuel is mined, enriched, fabricated, turned into electricity, reprocessed, and finally stored.
Now that you’ve had a chance to understand the six basic steps of the nuclear fuel cycle, let’s take a moment for a quick review.

It's important for you to understand the cycle in order to participate in the follow-up questions, which will be more in-depth about the nuclear fuel cycle. If you want to go back and review before you move on to the next question, that’s fine.

Can you describe, in your own words, the process of producing and disposing of nuclear fuel?

____________________________________________________________________________________

____________________________________________________________________________________

____________________________________________________________________________________

____________________________________________________________________________________

____________________________________________________________________________________

Based on what you’ve learned, please circle if you agree or disagree with the following statements:

1. When uranium fissions it releases lots of energy (heat) that is used in a nuclear power plant to produce electricity...

   AGREE       DISAGREE

2. Once nuclear fuel is removed from the nuclear reactor it becomes “used fuel,” but it is possible to recycle this fuel and use it again in a nuclear reactor...

   AGREE       DISAGREE
Now you’re ready to learn even more and share your opinion through some fun exercises.
Now, we’re going to introduce four different factors related to the nuclear fuel cycle and ask you to assign a value to each. For example, what’s important to you, or what might drive you to choose one factor over another? Take a look at the four different factors and their descriptions below.

<table>
<thead>
<tr>
<th>1. <strong>MAXIMIZING BENEFITS</strong></th>
<th>2. <strong>MINIMIZING PHYSICAL LIABILITIES</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Such as reducing the amount of uranium we need to mine, or having more flexible options for disposal of nuclear fuel</td>
<td>Such as reducing the risk of accidents, or radiation exposure, or the probability of theft of nuclear materials</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. <strong>MINIMIZING IMPLEMENTATION LIABILITIES</strong></th>
<th>4. <strong>MINIMIZING COSTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Such as minimizing the time required to put a new process in place, or reducing the chance of delays during the implementation process</td>
<td>Such as managing the cost over the short-term, mid-term, or long-term</td>
</tr>
</tbody>
</table>

You’ll show us how important these are to you by allocating 100 points across these four factors. If something is more important to you, give it more points. If something is less important, give it less points. The only rule is that the points total 100 in the end. Don’t worry if you’re not quite sure – just go with your gut and do the best you can.

- **Maximizing Benefits:** 
  
- **Minimizing Physical Liabilities:** 
  
- **Minimizing Implementation Liabilities:** 
  
- **Minimizing Costs:** 

**TOTAL POINTS (must add up to 100):**
One down! Three to go!
We can use several technologies and processes to complete the six steps of the nuclear fuel cycle. We’re going to think about some considerations when it comes to evaluating possibilities in nuclear fuel cycles.

Every nuclear fuel cycle has certain inherent physical liabilities or risks.

These liabilities involve:

1. How the nuclear material is handled
2. The risk of accidents
3. The risk of radiation exposure
4. The risk of nuclear theft
Let’s start this section by better understanding the risks associated with accidents that may occur within a nuclear fuel cycle. As with any large industrial process, each nuclear fuel cycle has an inherent possibility of some type of accident occurring. However, the probability of these accidents occurring tends to be fairly small, and may increase as the nuclear fuel cycle becomes more complex.

There are generally two types of accidents that we would like for you to understand before we propose some more choices to you:

A **Level 6 or 7 accident** results in negative effects that are fairly widespread and/or potentially severe.

A **Level 4 or 5 accident** has consequences that tend to be less severe and/or that affect only the immediate vicinity around the accident site.
So now we want to give you some choices and have you evaluate these choices as you’ve done before. Remember that some scenarios will be an easy choice, others will be harder. Also remember that some scenarios may not seem very realistic, but we are trying to understand the amount of risk you are willing to tolerate.

Now, give **100 points** to the scenario that is most important to you, and give the other one fewer points, depending on how much less important it is to you. If it’s much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. It’s okay if the two scenarios are truly equal in importance – give both scenarios 100 points.

Here are the two scenarios:

**Choice A:**
There is a 40% probability that a **Level 6 or 7 accident** will occur, BUT there is **0% probability** that a **Level 4 or 5 accident** will happen.

**Choice B:**
There is a 40% probability that a **Level 4 or 5 accident** will occur, BUT there is **0% probability** that a **Level 6 or 7 accident** will happen.

☐ **CHECK:** did you give at least one scenario 100 points?
If yes, continue. If not, please review and give at least one scenario 100 points.
In order to fully understand how you feel about these types of accidents, we’re going to ask you to rate how acceptable these factors are at various levels. We’ll start by looking at the risk of a Level 6 or 7 accident, which is widespread and/or severe.

**On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle …**

<table>
<thead>
<tr>
<th>Completely Unacceptable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>…would have 0% probability of a Level 6 or 7 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 15% probability of a Level 6 or 7 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 25% probability of a Level 6 or 7 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 40% probability of a Level 6 or 7 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

And now think about Level 4 or 5 accidents, which are less severe and/or impact only the immediate vicinity.

**On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle …**

<table>
<thead>
<tr>
<th>Completely Unacceptable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>…would have 0% probability of a Level 4 or 5 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 15% probability of a Level 4 or 5 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 25% probability of a Level 4 or 5 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>…would have 40% probability of a Level 4 or 5 accident</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>
Another risk that we mentioned has to do with the risk of radiation exposure, either to workers in the nuclear facilities where the nuclear fuel cycle takes place, or to the general public. Let’s learn more about that so that you can evaluate this risk.

Radiation is naturally everywhere. The amount of natural radiation we are exposed to varies from location to location, depending on elevation, soil content, and the foods we eat. In addition to natural sources of radiation, exposure may also occur when we have some medical procedures, travel long distances by plane, or when we come in close contact with nuclear material. Depending on different alternatives for nuclear fuel disposal, radiation exposure may occur, but different alternatives will offer different ways to minimize the risk of radiation exposure.

Based on this understanding, you’re ready to judge the scenarios related to radiation exposure. These may be hard, but just think about the types of risk that you are willing to tolerate. Again, give 100 points to the scenario that is most important to you, and give the other one fewer points, depending on how much less important it is to you. If it’s much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. It’s okay if the two scenarios are truly equal in importance – give both scenarios 100 points.

Here are the two scenarios:

**Choice A:**

The amount of radiation exposure for nuclear facility workers is increased by 50%, but the radiation exposure for the general public is decreased by 10%.

**Choice B:**

The amount of radiation exposure for nuclear facility workers is decreased by 10%, but the radiation exposure for the general public is increased by 50%.

☐ **CHECK:** Did you give at least one scenario 100 points?  
If yes, continue. If not, please review and give at least one scenario 100 points.
Again, we want to fully understand how you feel about these risks, so we would like for you to rate how acceptable these factors are at various levels. We'll start with the increase or decrease of radiation exposure affecting facility workers.

### On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle...

<table>
<thead>
<tr>
<th>Completely Unacceptable</th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...decrease radiation exposure to facility workers by 10%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...decrease radiation exposure to facility workers by 5%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...increase radiation exposure to facility workers by 25%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...increase radiation exposure to facility workers by 50%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
</tbody>
</table>

And now we'll talk about the increase or decrease of radiation exposure affecting the general public.

### On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle...

<table>
<thead>
<tr>
<th>Completely Unacceptable</th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...decrease radiation exposure to the general public by 10%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...decrease radiation exposure to the general public by 5%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...increase radiation exposure to the general public by 25%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>...increase radiation exposure to the general public by 50%</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
</tbody>
</table>
The final physical risk that we’re going to discuss is the risk of theft of nuclear materials. Each fuel cycle has an inherent possibility, even if it’s small, that some of the nuclear material used will be stolen. You see, uranium and the material needed to produce nuclear energy is scarce and limited in the world, which makes it valuable. In the worst case, this stolen material could be used by a terrorist organization in some form of a weapon. In the best case, the stolen material may be sold for medical purposes. The possibility of theft increases with complexity. So the more handling, processing, and transferring between facilities there is, the greater the possibility that theft may occur.

Given what you now know about the possibility of theft, please tell us how acceptable these probabilities of theft are to you.

| On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle... |
|---|---|---|---|---|---|---|---|---|---|
| ...have 0% probability of nuclear theft | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| ...have 5% probability of nuclear theft | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| ...have 15% probability of nuclear theft | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| ...have 20% probability of nuclear theft | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
You’ve learned a lot now about the three types of physical liabilities or risks:

1. The risk of an accident, either Level 6 or 7 which is more widespread and/or severe, or a Level 4 or 5 which is less severe and/or impacts the immediate vicinity – the chances of an accident ranges from 0% to 40%.

2. The risk of exposure, either to facility workers or the general public – exposure could decrease up to 10%, or increase up to 50%.

3. The risk of nuclear material being stolen – the chances of theft range from 0% to 20%.

Now we would like you to evaluate some scenarios involving these three kinds of risk. By now, you know the drill! This time we’ll have three scenarios to rate. Please think about the following scenarios and your opinion of each.

Give the scenario that is most important to you 100 points, and give the other ones fewer points, depending on how much less important they are to you. If a choice is much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. It’s okay if all of the scenarios are truly equal in importance – give all three choices 100 points.

Here are the three scenarios:

**Choice A:**
The probability that there will be Level 4, 5, 6, or 7 accident is 0%, BUT the radiation exposure for facility workers and the general public is increased by 50%, AND there’s a 20% chance of nuclear theft.

**Choice B:**
Radiation exposure for facility workers and the general public is decreased by 10%, BUT there is a 40% probability of an accident (either Level 4, 5, 6, or 7), AND there’s a 20% chance of nuclear theft.

**Choice C:**
There is no chance (0% probability) of nuclear theft, BUT there is a 40% probability of an accident (either Level 4, 5, 6, or 7), AND radiation exposure increases by 50% for both facility workers and the general public.

**CHECK:** did you give at least one scenario 100 points?
If yes, continue. If not, please review and give at least one scenario 100 points.
Halfway done!
Welcome back!

We’re learning a lot about your choices, which will help us to construct the best alternative for a nuclear fuel cycle for the United States. This next topic will be about HOW we implement that fuel cycle and make any necessary changes from the current approach today.

Choosing a fuel cycle will determine how it is implemented, and risks associated with such implementation. For example, if a fuel cycle is more technically complex and involves newer technology, it may require a longer implementation time. Additionally, certain unforeseen problems (technical, legal, political, etc.) may occur as the new fuel cycle is implemented, resulting in delays and roadblocks to putting the new fuel cycle in place.

Regarding the implementation time, each fuel cycle alternative will have a certain amount of time that is needed before it can be fully implemented and begin accepting nuclear fuel for final disposal. Factors that affect the length of time are of technological, regulatory, and logistical complexity.

Unforeseen problems may also occur during implementation. The probability of unforeseen problems increases with complexity of the fuel cycle. One example of unforeseen problems may involve acceptance of the fuel cycle from the general public. If acceptance is low, there may be additional delays and roadblocks which impede the fuel cycle from being implemented.
Taking into account both implementation time and the possibility of unforeseen delays, we would like you to evaluate these two scenarios. Remember that these scenarios may not seem very realistic, but what we’re trying to do is understand your overall risk tolerance.

Give the scenario that is most important to you 100 points, and give the other one fewer points, depending on how much less important it is to you. If it’s much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. If the two scenarios are truly equal in importance – give both scenarios 100 points.

Here are the two scenarios:

**Choice A:**
Full implementation of the new fuel cycle will take **50 years**, BUT there is no chance (**0% probability**) for unforeseen delays.

**Choice B:**
Full implementation of the new fuel cycle will be **effective immediately**, BUT there is a **100% probability** for unforeseen delays.

☐ **CHECK:** did you give at least one scenario 100 points?
If yes, continue. If not, please review and give at least one scenario 100 points.
Implementation Time

Again, based on what you now know about the implementation time and risk of unforeseen delays, please tell us how acceptable various levels of these factors are. We’ll start by looking at the implementation time for a particular fuel cycle alternative.

On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle...

<table>
<thead>
<tr>
<th></th>
<th>Completely Unacceptable</th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...is effective immediately</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>...takes 10 years to implement</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>...takes 30 years to implement</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>...takes 50 years to implement</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
</tbody>
</table>

Now, let’s do the same thing, but for the risk of unforeseen delays.

On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle...

<table>
<thead>
<tr>
<th></th>
<th>Completely Unacceptable</th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...has a 0% chance of unforeseen delays</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>...has a 25% chance of unforeseen delays</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>... has a 50% chance of unforeseen delays</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>... has a 100% chance of unforeseen delays</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
</tbody>
</table>
All these choices and trade-offs have a price tag – you knew it was coming, didn’t you! Because a nuclear fuel cycle is a long-term project, there are many different ways to evaluate costs. For instance, some nuclear fuel cycles may have lower short-term costs, but higher overall long-term costs. Other fuel cycles may have higher short-term costs, but lower overall long-term costs.

We can think of the short-term as 10 years, while mid-term costs may accumulate over the first 30 years of implementation, and long-term costs have a 100-year view. So think about this in terms of yourself, and your family, and how the costs may be covered by different generations.

Thinking about those trade-offs in short- vs. mid- vs. long-term costs, we would like you to evaluate these three scenarios. Once again, give the scenario that is most important to you 100 points, and give the other ones fewer points, depending on how much less important they are to you. If a choice is much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. If you think all three scenarios are truly equal in importance – give all three scenarios 100 points.

Here are the three scenarios:

**Choice A:**
The nuclear fuel cycle will cost $5 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will be at $160 Billion, and over the long-term (100 years), the total cost will be $600 Billion.

**Choice B:**
The nuclear fuel cycle will cost $40 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will still be at $40 Billion (no additional costs incurred from years 10 to 30), and over the long-term (100 years), the total cost will be $600 Billion.

**Choice C:**
The nuclear fuel cycle will cost $40 Billion in the first 10 years. In the first 30 years of implementation, the cumulative costs will be at $160 Billion, but over the long-term (100 years), the total cost will be $160 Billion (no additional costs incurred from years 30 to 100).

☐ **CHECK:** did you give at least one scenario 100 points?  
If yes, continue. If not, please review and give at least one scenario 100 points.
We also want to know how acceptable these scenarios are to you in terms of the range of costs that may be incurred over the short-, mid-, and long-term. The range of costs may be larger or smaller over different time periods.

Starting with **short-term costs** (the first 10 years of implementation), on a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that the costs for a nuclear fuel cycle be...

<table>
<thead>
<tr>
<th>Cost ($ Billion)</th>
<th>Completely Unacceptable</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$15 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$30 Billion</td>
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<td>2</td>
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<td>4</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$40 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

For **mid-term costs** (the first 30 years of implementation), on a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that the cumulative costs for a nuclear fuel cycle be...

<table>
<thead>
<tr>
<th>Cost ($ Billion)</th>
<th>Completely Unacceptable</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$40 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$80 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>6</td>
<td>7</td>
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<td></td>
</tr>
<tr>
<td>$120 Billion</td>
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<td>2</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$160 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

And finally, thinking about the **long-term costs** (the first 100 years of implementation), on a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that the cumulative costs for a nuclear fuel cycle be...

<table>
<thead>
<tr>
<th>Cost ($ Billion)</th>
<th>Completely Unacceptable</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$160 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
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<td>10</td>
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<tr>
<td>$300 Billion</td>
<td>1</td>
<td>2</td>
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<td>4</td>
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<td>7</td>
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<td>10</td>
<td></td>
</tr>
<tr>
<td>$450 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$600 Billion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
Having a defined nuclear fuel cycle for the United States would have some tangible benefits. In general, we can break those benefits down into ones that have to do with:

- ones that are more about the flexibility of disposal of nuclear fuel

OR

- reducing the amount of new uranium that we need to mine

There may be other benefits that you can think of for having a clearly defined nuclear fuel cycle, but we’re going to focus on these two.
Let’s talk first about the benefit of flexibility for disposal purposes. Flexibility means having greater options for disposing of nuclear fuel, either because different types of fuel could be used or because different sizes and shapes of fuel rods could be accommodated.

This flexibility would allow us to manage all the types of fuel currently used in existing nuclear power plants, as well as any advanced nuclear fuels that may be developed in the future to improve safety and performance.

In the same manner, future advanced nuclear reactor designs may use nuclear fuel of different sizes or shapes than what we use today, thus a flexible process may be able to handle all of them.

We would like to know how you view flexibility when evaluating alternatives for disposal in a nuclear fuel cycle. Please think about the following scenarios and your opinion of each.

Again, give 100 points to the one that is most important to you, and give the other one fewer points, depending on how much less important it is to you. If it’s much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. If the two scenarios are truly equal in importance – give both scenarios 100 points.

Okay, here we go with our first set of scenarios:

**Choice A:**

The cycle is 100% flexible to accommodate any types of fuel, BUT disposal containers can only accommodate half (50%) of the sizes / shapes of fuel pellets and rods.

**Choice B:**

The cycle is 100% flexible so that disposal containers can accommodate any sizes/shapes of fuel, BUT the fuel cycle can only handle half (50%) of potential fuel types.

CHECK: did you give at least one scenario 100 points?

If yes, continue. If not, please review and give at least one scenario 100 points.
Now, we want to understand how you view different levels of flexibility based on the benefits of flexibility that we've discussed. We're going to ask you to rate how acceptable these factors are at various levels. We'll start by looking at the flexibility of a nuclear fuel cycle being able to accommodate different types of fuel.

On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle can accommodate...

<table>
<thead>
<tr>
<th></th>
<th>Completely Unacceptable</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...50% of all types of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...70% of all types of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...80% of all types of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...100% of all types of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

Now we'll do the same thing, but we want to understand your views on flexibility related to different sizes/shapes of fuel. On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle can accommodate...

<table>
<thead>
<tr>
<th></th>
<th>Completely Unacceptable</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Completely Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>...50% of all sizes / shapes of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...70% of all sizes / shapes of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...80% of all sizes / shapes of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>...100% of all sizes / shapes of fuel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
We mentioned that a second benefit of having a defined nuclear fuel cycle for the US could be to **reduce the amount of new uranium that we need to mine**. This would be driven by alternatives that allow more of the used fuel to be recycled each time it’s used. If less new fuel is required, less uranium would need to be mined domestically and abroad, which can have a positive environmental impact. Lowering the fuel requirements can also allow the US to achieve greater energy independence. And finally, reducing the amount of nuclear fuel required would also result in less nuclear waste. All in all, this would allow us to increase the amount of energy that we extract from the same amount of fuel.

We’re going to first find out more about how you feel about **reducing the amount of new uranium required** based on how much can be reused / recycled. We’re going to ask you to rate how acceptable this factor is at various levels. Some of these may seem obvious to you, but remember that you can use the 10-point scale to show how much more acceptable or unacceptable a level is.

On a scale of 1 to 10, with 1 being completely unacceptable to you, and 10 being completely acceptable to you, how acceptable is it that a nuclear fuel cycle...

<table>
<thead>
<tr>
<th>Completely Unacceptable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>...would not reduce the amount of new uranium required at all (0% can be reused/recycled)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>...would reduce the amount of new uranium required by 30% (30% can be reused/recycled)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>...would reduce the amount of new uranium required by 60% (60% can be reused/recycled)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>...would reduce the amount of new uranium required by 90% (90% can be reused/recycled)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>
And now, based on what you’ve learned about whether fuel cycles can be flexible, and also now that you know more about the benefits of new fuel reduction, we would like you to evaluate two more scenarios.

Please think about the following scenarios and your opinion of each. **Give the scenario that is most important to you 100 points, and give the other one fewer points, depending on how much less important it is to you.** If it’s much less important to you, then give it a much lower number of points. If it’s close, then maybe your less preferred option will only have a few less points. If the two scenarios are truly equal in importance – give both scenarios 100 points.

Here are the two scenarios:

**Choice A:**
The cycle is 100% completely flexible to accommodate **any types or sizes or shapes of fuel**, BUT the cycle would not reduce the amount of new uranium required at all (0% can be reused/recycled).

**Choice B:**
The cycle reuses or recycles **90% of the spent fuel**, BUT the fuel cycle **only works with 50% of the current types and sizes/shapes** of nuclear fuel which are already in use.

☑ **CHECK: did you give at least one scenario 100 points?**
If yes, continue. If not, please review and give at least one scenario 100 points.
The finish line is in sight...
Wrap Up!

You’ve now learned A LOT about nuclear fuel cycles. Congratulations! Now that you know so much more, we want to again take a look at how you may generally weigh different alternatives for nuclear fuel. Just like we did a little while ago, we want to see what’s important to you, or what might drive you to choose one alternative over another. Take a look at the four different factors and their descriptions below just to remind yourself and summarize all that you’ve learned.

<table>
<thead>
<tr>
<th>1. MAXIMIZING BENEFITS</th>
<th>2. MINIMIZING PHYSICAL LIABILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Such as reducing the amount of uranium we need to mine, or having more flexible options for disposal of nuclear fuel</td>
<td>Such as reducing the risk of accidents, or radiation exposure, or the probability of theft of nuclear materials</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. MINIMIZING IMPLEMENTATION LIABILITIES</th>
<th>4. MINIMIZING COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Such as minimizing the time required to put a new process in place, or reducing the chance of delays during the implementation process</td>
<td>Such as managing the cost over the short-term, mid-term, or long-term</td>
</tr>
</tbody>
</table>

Show us how important these are to you by allocating 100 points across the four factors. If something is more important to you as you evaluate alternatives, give it more points. If something is less important, give it less points. The only rule is that the points total 100 in the end.

Maximizing Benefits: __________________ [B]

Minimizing Physical Liabilities: __________________ [P]

Minimizing Implementation Liabilities: __________________ [I]

Minimizing Costs: __________________ [C]

**TOTAL POINTS (must add up to 100): __________________**
In Closing…

We have covered a lot of ground over these exercises. Thank you so much for sharing your opinions with us on this very complex topic!

How would you sum up what you’ve learned and how you feel about the choices and alternatives we’ve discussed?

Do you have any final comments that you would like to share with us?

Please clearly PRINT your first and last name, so we can be sure to give you credit for completing this workbook:

Before you mail your completed workbook in the envelope provided, please take a moment to review that you awarded points according to the specific directions on each page - there are slight differences that are easy to miss!

Thank you so much for your time and dedication! We appreciate all your thoughts on this very important topic.
Appendix E

VALUE FUNCTIONS

E.1 Economist Value Functions
E.2 Environmental Scientist Value Functions
E.3 General Public Value Functions
E.4 Nuclear Engineer and Scientist Value Functions
E.5 Political Scientist Value Functions

Political Scientist Values: B1

Political Scientist Values: B2

Political Scientist Values: B3

Political Scientist Values: C1

Political Scientist Values: C2

Political Scientist Values: C3

Political Scientist Values: I1

Political Scientist Values: I2
E.6 Weighted Value Functions

1. Weighted Value Functions: B1
   - Value vs. B1 Uranium Reduction (percent)

2. Weighted Value Functions: B2
   - Value vs. B2 Fuel Sizes (percent)

3. Weighted Value Functions: B3
   - Value vs. B3 Fuel Types (percent)

4. Weighted Value Functions: C1
   - Value vs. C1 Short term (billions of Dollars)

5. Weighted Value Functions: C2
   - Value vs. C3 Mid Term (billions of Dollars)

6. Weighted Value Functions: C3
   - Value vs. C3 Long Term (billions of Dollars)

7. Weighted Value Functions: I1
   - Value vs. I1 Time (years)

8. Weighted Value Functions: I2
   - Value vs. I1 Delays (percent)
Appendix F

DISTRIBUTIONS

F.1 A1 Distributions
F.2 A2 Distributions

Distribution for A2 on Objective B1

Distribution for A2 on Objective B2

Distribution for A2 on Objective B3

Distribution for A2 on Objective C1

Distribution for A2 on Objective C2

Distribution for A2 on Objective C3

Distribution for A2 on Objective I1

Distribution for A2 on Objective I2
F.3 A3 Distributions
F.4 A4 Distributions

- Distribution for A4 on Objective B1
- Distribution for A4 on Objective B2
- Distribution for A4 on Objective B3
- Distribution for A4 on Objective C1
- Distribution for A4 on Objective C2
- Distribution for A4 on Objective C3
- Distribution for A4 on Objective I1
- Distribution for A4 on Objective I2
F.5 A5 Distributions

Distribution for A5 on Objective B1

Distribution for A5 on Objective B2

Distribution for A5 on Objective B3

Distribution for A5 on Objective C1

Distribution for A5 on Objective C2

Distribution for A5 on Objective C3

Distribution for A5 on Objective I1

Distribution for A5 on Objective I2
F.6 A6 Distributions

- Distribution for A6 on Objective B1
- Distribution for A6 on Objective B2
- Distribution for A6 on Objective B3
- Distribution for A6 on Objective C1
- Distribution for A6 on Objective C2
- Distribution for A6 on Objective C3
- Distribution for A6 on Objective I1
- Distribution for A6 on Objective I2
F.7 A7 Distributions

- Distribution for A7 on Objective B1
- Distribution for A7 on Objective B2
- Distribution for A7 on Objective B3
- Distribution for A7 on Objective C1
- Distribution for A7 on Objective C2
- Distribution for A7 on Objective C3
- Distribution for A7 on Objective I1
- Distribution for A7 on Objective I2
F.8 A8 Distributions

Distribution for A8 on Objective B1

Distribution for A8 on Objective B2

Distribution for A8 on Objective B3

Distribution for A8 on Objective C1

Distribution for A8 on Objective C2

Distribution for A8 on Objective C3

Distribution for A8 on Objective I1

Distribution for A8 on Objective I2
F.9 A9 Distributions

- Distribution for A9 on Objective B1
- Distribution for A9 on Objective B2
- Distribution for A9 on Objective B3
- Distribution for A9 on Objective C1
- Distribution for A9 on Objective C2
- Distribution for A9 on Objective C3
- Distribution for A9 on Objective I1
- Distribution for A9 on Objective I2
Distribution for A9 on Objective P1

Distribution for A9 on Objective P2

Distribution for A9 on Objective P3

Distribution for A9 on Objective P4

Distribution for A9 on Objective P5
F.10 A10 Distributions

Distribution for A10 on Objective B1

Distribution for A10 on Objective B2

Distribution for A10 on Objective B3

Distribution for A10 on Objective C1

Distribution for A10 on Objective C2

Distribution for A10 on Objective C3

Distribution for A10 on Objective I1

Distribution for A10 on Objective I2
Appendix G

PYTHON CODES

G.1 Individual Stakeholders

# coding: utf-8

# In[2]:

get_ipython().magic('matplotlib inline')
import numpy as np
import xlrd
import matplotlib.pyplot as plt
import numpy.random as rand

#Imports data from the accompanying spreadsheet
#you will probably need to change this path
file = 'J:/Thesis.Model.Data/Econ.xlsx'
#
workbook = xlrd.open_workbook(file)
sheetgenpub = workbook.sheet_by_index(4) #Change This for a new Stakeholder.

# 0 = Economist 1 = General Public 2 = Environmental Scientist 3 = Nuclear Scientists 4 = Political Scientists

weights = [sheetgenpub.cell_value(1, c) for c in range(20)] # grabs the weights

simpleobj = [sheetgenpub.cell_value(12, c) for c in range(13)]
    # grabs objective names for making figures

alternatives = [A1, A2, A3, A4, A5, A6, A7, A8, A9, A10]

objectives = [sheetgenpub.cell_value(0, c) for c in range(13)]
    # objectives with explanation and measure

scores = [None]*10
valsimple = [[[for y in range(13)]for x in range(10)]#will be used to put evaluated value functions in

totalscore = [None]*10 #used to collect scores for each objective

carlo=[[for x in range(10)]#used to keep all the runs together for MonteCarlo Analysis
AvgScores = [None]*10  #average of each 'carlo' for each objective
b = [None]*10  #holds random scores for use

# In[3]:

#Used to randomize scores from experts on each objective.

Use 'rand.triangular' for randomized values or
# regular lists for the mode values

def randscores():
    a = {
        1 : [rand.triangular(0,2,4),rand.triangular(77,98.4,100),rand.triangular(76.6,95,98),
             rand.triangular(6.625,9.375,11.875),rand.triangular(22.5,40,55),rand.triangular(100.63,162.5,206),
             rand.triangular(2,9,10),rand.triangular(0,5,17.5),rand.triangular(0,4.5,10),rand.triangular(2,10.1,16.4),
             rand.triangular(0,2.4,5.1),rand.triangular(-2,3,8),rand.triangular(-6,0,6)],
        2 : [rand.triangular(0,2,4),rand.triangular(77,97.4,100),rand.triangular(72.6,94,98),rand.triangular(14.38,18.13,21.88),rand.triangular(49.25,68.75,92.5),rand.triangular}
(160,212.5,272.5), rand. triangular (2,9,10), rand. triangular (12.5,31.25,63), rand. triangular (0,3.5,8), rand. triangular (2,9.3,15.4), rand. triangular (0,3.9,8.6), rand. triangular (3,11,19.6), rand. triangular (−8,−2,4.4)],
3 : [rand. triangular (0,2,4), rand. triangular (74.4,94,97.4), rand. triangular (66,89.6,96), rand. triangular (19.38,25.63,31.88), rand. triangular (62.5,86.88,123.75), rand. triangular (218.75,286.28,378.75), rand. triangular (10,25.5,40), rand. triangular (17.5,58.75,88.75), rand. triangular (2.4,6.7,11.2), rand. triangular (5.8,12.7,18.4), rand. triangular (0,3.9,8.6), rand. triangular (3,11,19), rand. triangular (−6,0,5.4)
],
4 : [rand. triangular (1.4,9,13), rand. triangular (74,93.5,97.4), rand. triangular (66,89.6,96), rand. triangular (21.25,28.75,35), rand. triangular (68.13,100,135.63), rand. triangular (248.75,333.75,443.75), rand. triangular (15,28.4,43.5), rand. triangular (22.5,61.25,91.25), rand. triangular (3.4,8.1,12.5), rand. triangular (6.8,14.1,19.4), rand. triangular (0.2,3.9,9.2), rand. triangular (4,12.6,21), rand. triangular (−5,0,6.4)],
5: [rand.triangular(2,5,7), rand.triangular(74,93.5,97.4), rand.triangular(66,89.4,96), rand.triangular(17.5,21.25,27), rand.triangular(55.75,71.88,102.5), rand.triangular(197.75,236.25,303.75), rand.triangular(11,26.2,47), rand.triangular(12.5,58.75,88.75), rand.triangular(1.6,5.1,10.4), rand.triangular(3.8,10.1,18), rand.triangular(0.6,3.9,9.6), rand.triangular(3,10,21), rand.triangular(-6,0,5.4)],
6: [rand.triangular(1.4,9,13), rand.triangular(73.6,93.4,97), rand.triangular(66,89,96), rand.triangular(19.38,24.38,30.13), rand.triangular(64.67,95.83,125), rand.triangular(212.5,275,337.5), rand.triangular(15,27.6,48), rand.triangular(17.5,61.25,91.25), rand.triangular(2.8,5.9,10.6), rand.triangular(4,13.1,19), rand.triangular(0.2,3.9,8.1), rand.triangular(4,11,21), rand.triangular(-6,0,7)],
7: [rand.triangular(0,4,8), rand.triangular(64.6,87.6,91), rand.triangular(62.4,85.6,89.4), rand.triangular(16.88,24.38,34.25), rand.triangular(55.17,83,120.83), rand.triangular(166.67,266.67,350), rand.triangular(14.5,32,44), rand.triangular(22.5,70,93.75), rand.triangular(204)]
(1.4, 5.7, 10.4), rand. triangular (3, 8.9, 16), rand. triangular (0.2, 3.6), rand. triangular (3, 10, 20),
rand. triangular (−8, −2.4.4)],
8: [rand. triangular (15, 34, 46), rand. triangular (64, 72.6, 87), rand. triangular (40, 61.6, 79.6), rand. triangular (19.38, 24.38, 30.63), rand. triangular (75, 104.13, 133.33), rand. triangular (233.33, 366.67, 466.67), rand. triangular (9, 24, 37), rand. triangular (15, 52.5, 89.25), rand. triangular (4, 9.8, 18), rand. triangular (7, 17, 26), rand. triangular (3, 11, 19.4), rand. triangular (5, 18, 32), rand. triangular (−2, 4), 11],
9: [rand. triangular (14.4, 34, 46), rand. triangular (55, 73, 88), rand. triangular (46, 68, 86), rand. triangular (28.13, 34.38, 45.37), rand. triangular (58.83, 100, 131.67), rand. triangular (241.67, 325, 423.33), rand. triangular (17, 31, 43), rand. triangular (20, 58.75, 91.25), rand. triangular (1.4, 6.8, 13.6), rand. triangular (2, 11.8, 20.8), rand. triangular (3, 11, 18.5), rand. triangular (5, 20, 36), rand. triangular (−2, 3, 8.6)],
10: [rand. triangular (38, 69, 87.2), rand. triangular (57, 75.8, 88), rand. triangular (50, 73, 88.8), rand. triangular (28.13, 38.13, 53.13), rand. triangular (133.3, 176.67, 220.83), rand. triangular
(341.67, 458.33, 575), rand. triangular
(23, 36, 49.25), rand. triangular (22.5, 63.25, 93.75)
, rand. triangular (4.4, 12.4, 28.2), rand. triangular
(6, 21, 37.5), rand. triangular (3, 10.8, 18.5), rand. triangular
(13, 28, 43), rand. triangular (−2, 6, 16)]

# Uncomment for average values
# a = {
#   1 :
#   [2, 98.4, 95, 9.375, 40, 162.5, 9, 5, 4.5, 10.1, 2.4, 3, 0],
#   2 :
#   [2, 97.4, 94, 18.13, 68.75, 212.5, 26, 31.25, 3.5, 9.3, 3.9, 11, −2],
#   3 :
#   [2, 94, 89.6, 25.63, 86.88, 286.28, 25.5, 58.75, 6.7, 12.7, 3.9, 11, 0],
#   4 :
#   [9, 93.5, 89.6, 28.75, 100, 333.75, 28.4, 61.25, 8.1, 14.1, 3.9, 12.6, 0],
#   5 :
#   [5, 93.5, 89.4, 21.25, 71.88, 236.25, 26.2, 58.75, 5.1, 10.1, 3.9, 10, 0],
#   6 :
#   [9, 93.4, 89, 24.38, 95.83, 275, 27.6, 61.25, 5.9, 13.1, 3.9, 11, 0],
#   7 :
#   [4, 87.6, 85.6, 24.38, 83, 266.67, 32, 70, 5.7, 8.9, 3, 10, −2.4],

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def calculations(a):
    for i in range(1, 11):
        b[i-1] = a[i]
        # b is the scores at beginning of each calculation

genpubx = [sheetgenpub.cell_value(5, c) for c in range(52)]
genpuby = [sheetgenpub.cell_value(9, c)/10 for c in range(52)]
t = []
g=[None]*10 # output
for i in range(13):
    genpuby[i] = genpuby[4*i:4+4*i]
genpubx[i] = genpubx[4*i:4+4*i]

for r in range(10):
    for i in range(13):
        t.append(np.interp(b[r][i], genpubx[i], genpuby[i]))

for i in range(10):
    g[i] = t[13*i:13+13*i]

for i in range(10):
    for j in range(13):
        valsimple[i][j] = g[i][j]*weights[j]

#Level 2 Weights
for i in range(10):
    scores[i] = {'cost': weights[17]*( sum(valsimple[i][3:6]) ),
                 'ben': weights[16]*( valsimple[i][0] + weights[15]*( sum(valsimple[i][1:3]) ) ),
                 'phy': weights[19]*( weights[13]*( sum(valsimple[i][8:10]) + weights[14]*( sum(valsimple[i][11:13]) + valsimple[i][10] ) ) ),
                 'imp': weights[18]*( sum(valsimple[i][6:8]) )}

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# Sums everything

```python
for i in range(10):
    totalscore[i] = sum(scores[i].values())
```

# Adds scores to giant list for Monte Carlo

```python
for i in range(10):
    carlo[i].append(totalscore[i])
```

# Defines Monte Carlo

```python
def Monte(runs):
    for i in range(runs):
        a = randscores()
        calculations(a)
    for i in range(10):
        AvgScores[i] = np.mean(carlo[i])
```

```python
for i in range(10):
    print(alternatives[i], AvgScores[i])
```

# Enter number of runs

Monte(10)

# In[4]:

# Stacked Bar Graphs

# Don’t forget to change
```python
linspace = np.arange(len(alternatives))
width = 1/1.5
ben = np.array([scores[i]["ben"] for i in range(10)])
cost = np.array([scores[i]["cost"] for i in range(10)])
phy = np.array([scores[i]["phy"] for i in range(10)])
imp = np.array([scores[i]["imp"] for i in range(10)])

benefits = plt.bar(linspace, ben, width, label='Benefits')
costs = plt.bar(linspace, cost, width, bottom=ben, color='r',
                 label='Costs')
physical = plt.bar(linspace, phy, width, bottom=ben+cost, color='y',
                   label="Physical")
implementation = plt.bar(linspace, imp, width, bottom=ben+cost+phy,
                        color='w', label='Implementation')
plt.ylabel('Value')
plt.legend(bbox_to_anchor=(1, 1), loc='upper left', ncol=1)
plt.xticks(linspace+.3, alternatives)
plt.title('Environmental Scientists: Stacked Bar Chart')
# plt.savefig('EnvStack.png', bbox_inches='tight')
plt.plot()
```
# In[5]:

# Value Functions

```
# grabs all the values for utility functions from spreadsheet
genpuby = [sheetgenpub.cell_value(9, c)/10 for c in range(52)]
genpubx = [sheetgenpub.cell_value(5, c) for c in range(52)]

# groups values into nested lists based on objective
for i in range(13):
genpuby[i] = genpuby[4*i:4+4*i]
genpubx[i] = genpubx[4*i:4+4*i]

# gets rid of excess values in list
del genpubx[13:]
del genpuby[13:]

for i in range(13):
    plt.plot(genpubx[i], genpuby[i])
    plt.title('General/Public: ' + simpleobj[i])
    plt.ylabel('Value')
```
plt.xlabel(objectives[i])
plt.grid()
# plt.savefig('Pol'+str(i+1)+'.png')
plt.show()

# In[6]:

# Value Gaps # DON'T FORGET TO CHANGE TITLES AND FILENAMES

arr=[None]*10#will be used to hold scores for each broad category
Objs = ['Benefits', 'Costs', 'Implementation', 'Physical']

for i in range(10):
    arr[i]=np.array([scores[i]["ben"], scores[i]["cost"], scores[i]["imp"], scores[i]["phy"]])

linspace = np.arange(len(arr[0]))
width = 1/1.5

ben = np.array([[scores[i]["ben"] for i in range(10)]]

cost = np.array([[scores[i]["cost"] for i in range(10)]]

phy = np.array([[scores[i]["phy"] for i in range(10)]]

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imp = np.array([scores[i][‘imp’] for i in range(10)])

for j in range(10):
    # Stacked Bar Graphs
    costs = plt.bar(linspace, weights[16:], width, color=’w’,
                     label=’Value Gap’)
    benefits = plt.bar(linspace, arr[j], width, label=’A’+str(j+1), color=’black’)
    plt.ylabel(’Value’)
    plt.legend(bbox_to_anchor=(1, 1), loc=’upper left’, ncol=1)
    plt.xticks(linspace+.3, Obj)
    plt.title(’Political Scientists: Value Gap A’ + str(j+1))
    plt.savefig(’PolValGap’+str(j+1)+’.png’, bbox_inches=’tight’)
    plt.show()

# In[7]:

# Cost Benefit

# DON’T FORGET TO CHANGE TITLES AND FILENAMES

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linspace = np.arange(len(alternatives))
width = 1/1.5

ben = np.array([scores[i]["ben"] for i in range(10)])
cost = np.array([scores[i]["cost"] for i in range(10)])
phy = np.array([scores[i]["phy"] for i in range(10)])
imp = np.array([scores[i]["imp"] for i in range(10)])

x=[scores[i]["cost"]+scores[i]["phy"]+scores[i]["imp"] for i in range(10)]
y=[scores[i]["ben"] for i in range(10)]

# Cost Ben Scatter
plt.scatter(x,y)
plt.xlabel('Total "Cost" Value')
plt.ylabel('Benefit Value')
plt.title('Environmental Scientists: Cost Vs. Benefit')

for i, txt in enumerate(alternatives):
    plt.annotate(txt, (x[i]+.005, y[i]))

# plt.savefig('EnvCostBen'+'.png')
plt.grid(True)
plt.plot()
G.2 Summed Stakeholders

# In[13]:

get_ipython().magic('matplotlib inline')
import xlrd
import numpy as np
import matplotlib.pyplot as plt
import numpy.random as rand

# In[14]:

file_location = 'J:/Thesis.Model.Data/Econ.xlsx' #Change this path as appropriate
workbook = xlrd.open_workbook(file_location)
#Define sheets for each stakeholder
sheetec = workbook.sheet_by_index(0)
sheetgenpub = workbook.sheet_by_index(1)
sheetenv = workbook.sheet_by_index(2)
sheetnuc = workbook.sheet_by_index(3)
sheetpol = workbook.sheet_by_index(4)
# import weights for each stakeholder

econw = [sheetcon.cell_value(1,c) for c in range(20)]
genw = [sheetgenpub.cell_value(1,c) for c in range(20)]
enw = [sheetenv.cell_value(1,c) for c in range(20)]
nucw = [sheetnuc.cell_value(1,c) for c in range(20)]
polw = [sheetpol.cell_value(1,c) for c in range(20)]
simpleobj = [sheetgenpub.cell_value(12,c) for c in range(13)]
objectives = [sheetgenpub.cell_value(0,c) for c in range(13)]

# Create Variables
scores = [None]*10
valsimple = [[[None] for y in range(13)] for x in range(10)]
totalscore = [None]*10
carlo = [[None] for x in range(10)]
AvgScores = [None]*10
g = []

# import value functions for each stakeholder
x = [sheetcon.cell_value(5,c) for c in range(52)]  # x values
for each value function
econy = [sheetcon.cell_value(9,c)/10 for c in range(52)]
genpuby = [sheetgenpub.cell_value(9,c)/10 for c in range(52)]
envy = [sheenenv.cell_value(9,c)/10 for c in range(52)]
poly = [sheetpol.cell_value(9,c)/10 for c in range(52)]
nucy = [sheatnuc.cell_value(9,c)/10 for c in range(52)]

#averaging weights and value functions
weights = [None] * 20
values = [None] * 52

#Add to this as more information becomes available

for i in range(20):
    weights[i] = .0955 * econw[i] + .0764 * genw[i] + .3658 * envw[i] + .3679 * nucw[i] + .0944 * polw[i]

for i in range(52):
    values[i] = .0955 * econy[i] + .0764 * genpuby[i] + .3658 * envy[i] + .3679 * nucy[i] + .0944 * poly[i]

for i in range(13):
    values[i] = values[4*i:4+4*i]
    x[i] = x[4*i:4+4*i]

delete values[13:]
delete x[13:]
# Polynomial fitting

valuesz = [None]*13
valuesp = [None]*13
for i in range(13):
    valuesz[i] = np.polyfit(x[i], values[i], 2)
    valuesp[i] = np.poly1d(valuesz[i])

# Linear Fitting
#
# valuesz[i] = np.polyfit(x[i], values[i], 1)
# valuesp[i] = np.poly1d(valuesz[i])

def randscores():
    # a = {
    # 1 : [rand.triangular(0,2,4),rand.triangular
    # (77,98.4,100),rand.triangular(76.6,95,98),rand.triangular
    # (6.625,9.375,11.875),rand.triangular(22.5,40,55),rand.
    # triangular(100.63,162.5,206),rand.triangular(2,9,10),rand.
    # triangular(0,5,17.5),rand.triangular(0,4.5,10),rand.
    # triangular(2,10.1,16.4),rand.triangular(0,2.4,5.1),rand.
triangular(−2,3,8), rand. triangular(−6,0,6)],

# 2 : [rand. triangular(0,2,4), rand. triangular
(77,97.4,100), rand. triangular(72.6,94,98), rand. triangular
(14.38,18.13,21.88), rand. triangular(49.25,68.75,92.5), rand.
. triangular(160,212.5,272.5), rand. triangular(2,9,10), rand.
. triangular(12.5,31.25,63), rand. triangular(0,3.5,8), rand.
. triangular(2,9.3,15.4), rand. triangular(0,3.9,8.6), rand.
. triangular(3,11,19.6), rand. triangular(−8,−2,4.4)],

# 3 : [rand. triangular(0,2,4), rand. triangular
(74.4,94,97.4), rand. triangular(66,89.6,96), rand. triangular
(19.38,25.63,31.88), rand. triangular(62.5,86.88,123.75),
rand. triangular(218.75,286.28,378.75), rand. triangular
(10,25.5,40), rand. triangular(17.5,58.75,88.75), rand.
. triangular(2.4,6.7,11.2), rand. triangular(5.8,12.7,18.4),
rand. triangular(0,3.9,8.6), rand. triangular(3,11,19), rand.
. triangular(−6,0,5.4)],

# 4 : [rand. triangular(1.4,9,13), rand. triangular
(74,93.5,97.4), rand. triangular(66,89.6,96), rand. triangular
(21.25,28.75,35), rand. triangular(68.13,100,135.63), rand.
triangular(248.75,333.75,443.75), rand. triangular
(15,28.4,43.5), rand. triangular(22.5,61.25,91.25), rand.
. triangular(3.4,8.1,12.5), rand. triangular(6.8,14.1,19.4),
rand. triangular(0.2,3.9,9.2), rand. triangular(4,12.6,21),
rand. triangular(−5,0,6.4)],

# 5 : [rand. triangular(2,5,7), rand. triangular
(74, 93.5, 97.4), rand. triangular (66, 89.4, 96), rand. triangular 
(17.5, 21.25, 27), rand. triangular (55.75, 71.88, 102.5), rand. 
triangular (197.75, 236.25, 303.75), rand. triangular 
(11, 26.2, 47), rand. triangular (12.5, 58.75, 88.75), rand. 
triangular (1.6, 5.1, 10.4), rand. triangular (3.8, 10.1, 18), rand 
. triangular (0.6, 3.9, 9.6), rand. triangular (3, 10, 21), rand. 
triangular (−6, 0, 5.4)],

# 6 : [rand. triangular (1.4, 9, 13), rand. triangular 
(73.6, 93.4, 97), rand. triangular (66, 89.96), rand. triangular 
(19.38, 24.38, 30.13), rand. triangular (64.67, 95.83, 125), rand. 
triangular (212.5, 275, 337.5), rand. triangular (15, 27.6, 48), 
rand. triangular (17.5, 61.25, 91.25), rand. triangular 
(2.8, 5.9, 10.6), rand. triangular (4, 13.1, 19), rand. triangular 
(0.2, 3.9, 8.1), rand. triangular (4, 11, 21), rand. triangular 
(−6, 0, 7)],

# 7 : [rand. triangular (0, 4, 8), rand. triangular 
(64.6, 87.6, 91), rand. triangular (62.4, 85.6, 89.4), rand. 
triangular (16.88, 24.38, 34.25), rand. triangular 
(55.17, 83, 120.83), rand. triangular (166.67, 266.67, 350), rand. 
triangular (14.5, 32.44), rand. triangular (22.5, 70, 93.75), rand 
. triangular (1.4, 5.7, 10.4), rand. triangular (3.8, 9, 16), rand. 
triangular (0.2, 3, 6), rand. triangular (3, 10, 20), rand. 
triangular (−8, −2.4, 4)],

# 8 : [rand. triangular (15, 34, 46), rand. triangular (64, 
72.6, 87), rand. triangular (40, 61.6, 79.6), rand. triangular
(19.38, 24.38, 30.63), rand.triangular(75, 104.13, 133.33), rand.triangular(233.33, 366.67, 466.67), rand.triangular(9, 24, 37), rand.triangular(15, 52.5, 89.25), rand.triangular(4, 9.8, 18), rand.triangular(7, 17, 26), rand.triangular(3, 11, 19.4), rand.triangular(5, 18, 32), rand.triangular(−2, 4, 11)]

9 : [rand.triangular(14.4, 34, 46), rand.triangular(55, 73, 88), rand.triangular(46, 68, 86), rand.triangular(28.13, 34.38, 45.37), rand.triangular(58.83, 100, 131.67), rand.triangular(241.67, 325.0, 423.33), rand.triangular(17, 31, 43), rand.triangular(20, 58.75, 91.25), rand.triangular(1.4, 6.8, 13.6), rand.triangular(2, 11.8, 20.8), rand.triangular(3, 11, 18.5), rand.triangular(5, 20, 36), rand.triangular(−2, 3, 8.6)]

10 : [rand.triangular(38, 69, 87.2), rand.triangular(57, 75.8, 88), rand.triangular(50, 73, 88.8), rand.triangular(28.13, 38.13, 53.13), rand.triangular(133.3, 176.67, 220.83), rand.triangular(341.67, 458.33, 575), rand.triangular(23, 36, 49.25), rand.triangular(22.5, 63.25, 93.75), rand.triangular(4.4, 12.4, 28.2), rand.triangular(6, 21, 37.5), rand.triangular(3, 10.8, 18.5), rand.triangular(13, 28, 43), rand.triangular(−2, 6, 16)]

#Uncomment for average values

221
\[ a = \{ \\
1 : \\
\quad [2, 98.4, 95, 9.375, 40, 162.5, 9, 5, 4.5, 10.1, 2.4, 3, 0], \\
2 : \\
\quad [2, 97.4, 94, 18.13, 68.75, 212.5, 26, 31.25, 3.5, 9.3, 3.9, 11, -2], \\
3 : \\
\quad [2, 94, 89.6, 25.63, 86.88, 286.28, 25.5, 58.75, 6.7, 12.7, 3.9, 11, 0], \\
4 : \\
\quad [9, 93.5, 89.6, 28.75, 100, 333.75, 28.4, 61.25, 8.1, 14.1, 3.9, 12.6, 0], \\
5 : \\
\quad [5, 93.5, 89.4, 21.25, 71.88, 236.25, 26.2, 58.75, 5.1, 10.1, 3.9, 10, 0], \\
6 : \\
\quad [9, 93.4, 89, 24.38, 95.83, 275, 27.6, 61.25, 5.9, 13.1, 3.9, 11, 0], \\
7 : \\
\quad [4, 87.6, 85.6, 24.38, 83, 266.67, 32, 70, 5.7, 8.9, 3, 10, -2.4], \\
8 : \\
\quad [34, 72.6, 61.6, 24.38, 104.13, 366.67, 24, 52.5, 9.8, 17, 11, 18, 4], \\
9 : \\
\} \\
222 \]
def calculations(a):
    # Putting initial scores through value functions
    initscores = [None]*10
    val = []
    g=[None]*10
    t=[]
    for i in range (1,11):
        initscores[i−1] = a[i]
        # for i in range(13):
        #     for j in range(10):
        #         val.append(valuesp[j](initscores[j][i]))
        #     # Weighting the 13 base objectives
        #     for i in range(10):
        #         val[i] = val[13*i:13+13*i]
for r in range(10):
    for i in range(13):
        t.append(np.interp(initScores[r][i], x[i], values[i]))

for i in range(10):
    g[i] = t[13*i:13+13*i]

#Level 1 Weights
for i in range(10):
    for j in range(13):
        valsimple[i][j] = g[i][j]*weights[j]

#Level 2 Weights
for i in range(10):
    scores[i] = {
        'cost': weights[17]*(sum(valsimple[i][3:6])),
        'ben': weights[16]*(valsimple[i][0]+weights[15]*(sum(valsimple[i][1:3])))
        'phy': weights[19]*(weights[13] *(sum(valsimple[i][8:10]) +
                                weights[14]*(sum(valsimple[i][11:13])+valsimple[i][10])))
        'imp': weights[18]*(sum(valsimple[i][6:8]))
    }

#Sums everything
for i in range(10):
    totalscore[i] = sum(scores[i].values())

# Adds scores to giant list for Monte Carlo
for i in range(10):
carlo[i].append(totalscore[i])

def Monte(runs):
    for i in range(runs):
a = randscores()
calculations(a)
    for i in range(10):
        AvgScores[i] = np.mean(carlo[i])

    for i in range(10):
        print(alternatives[i], AvgScores[i])

Monte(1)

# In[17]:
linspace = np.arange(len(alternatives))
width = 1/1.5
ben = np.array([scores[i]['ben'] for i in range(10)])
cost = np.array([scores[i]['cost'] for i in range(10)])
phy = np.array([scores[i][ 'phy'] for i in range(10)])
imp = np.array([scores[i][ 'imp'] for i in range(10)])

# Stacked Bar Graphs
benefits = plt.bar(linspace, ben, width, label='Benefits')
costs = plt.bar(linspace, cost, width, bottom=ben, color='r', label='Costs')
physical=plt.bar(linspace, phy, width, bottom=ben+cost, color='y', label="Physical")
implementation=plt.bar(linspace, imp, width, bottom=ben+cost+phy, color='w', label='Implementation')
plt.ylabel('Value')
plt.legend(bbox_to_anchor=(1, 1), loc='upper left', ncol=1)
plt.xticks(linspace+.3, alternatives)
plt.title('Weighted: Stacked Bar Chart')
plt.savefig('WeightedStack+.png',bbox_inches='tight')
plt.plot()

# In[18]:

linspace = np.arange(len(alternatives))
ben = np.array([scores[i]['ben'] for i in range(10)])
cost = np.array([scores[i]['cost'] for i in range(10)])
phy = np.array([scores[i]['phy'] for i in range(10)])
imp = np.array([scores[i]['imp'] for i in range(10)])
x=[scores[i]['cost']+scores[i]['phy']+scores[i]['imp'] for i in range(10)]
y=[scores[i]['ben'] for i in range(10)]

# Cost Ben Scatter
plt.scatter(x,y)
plt.xlabel('Total "Cost" Value')
plt.ylabel('Benefit Value')
plt.title('Weighted: "Cost" Vs. "Benefit"')

for i, txt in enumerate(alternatives):
    plt.annotate(txt,(x[i]+.005,y[i]))

plt.savefig('WeightedCostBen+.png')
plt.grid(True)
plt.plot()

# In[19]:

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width = 1/1.5
ben = np.array([scores[i][‘ben’] for i in range(10)])
cost = np.array([scores[i][‘cost’] for i in range(10)])
phy = np.array([scores[i][‘phy’] for i in range(10)])
imp = np.array([scores[i][‘imp’] for i in range(10)])
arr=[None]*10
for i in range(10):
    arr[i]=np.array([scores[i][‘ben’], scores[i][‘cost’], scores[i][‘imp’], scores[i][‘phy’]])
linspace = np.arange(len(arr[0]))
for j in range(10):
    #Stacked Bar Graphs
costs = plt.bar(linspace, weights[16:], width, color=‘w’, label=‘Value Gap’)
benefits = plt.bar(linspace, arr[j], width, label=‘A’+str(j+1), color=‘black’)

plt.ylabel(‘Value’)  
plt.legend(bbox_to_anchor=(1, 1), loc=’upper left’, ncol=1)
plt.xticks(linspace+.3, Objs)
plt.title(‘Weighted: Value Gap A’ + str(j+1))
# In[3]:

```python
for i in range(13):
    plt.plot(x[i], values[i])
    plt.title('Weighted Value Functions: ' + simpleobj[i])
    plt.ylabel('Value')
    plt.xlabel(objectives[i])
    plt.grid()
    # plt.savefig('Weighted' + str(i+1) + '.png')
    plt.show()
```

# In[ ]:
Stephen Godfrey Clement was born on May 14, 1989 in Buffalo, New York and is a citizen of the United States of America. He graduated from Frontier High School in Hamburg, New York in 2007. He received a Bachelor’s Degree in Physics and Physics Education from State University of New York College at Buffalo in 2011 graduating Summa Cum Laude. Following his graduation, he worked as a physics and math teacher at Culpeper High School where he was nominated for teacher of the year in 2014. He then worked a short stint at North Stafford High School teaching engineering and physics before he was presented with a great opportunity to work for Virginia Commonwealth University and further his education. While studying at VCU his work has been published at the 2016 ANS Student Conference and has been accepted to the 2017 International High-Level Radioactive Waste Management Conference.