VOTE FORECASTING THROUGH MULTI-OBJECTIVE DECISION ANALYSIS:
THE UNITED STATES – MEXICO BORDER DISPUTE

THESIS

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Abstract
In December 2018, the United States Federal Government began what would become the longest government shutdown in U.S. history. This was the 21st shutdown since the adoption of the current appropriations process and 4th of the last decade. These shutdowns occur after government departments and agencies submit budget requests to Congress and the legislature is unable to come to an agreement to pass an appropriations bill. There is no clear solution to this problem. But this study hypothesizes that government departments and agencies could benefit from considering the political viability of their own budget requests prior to submitting them to Congress. In the field of decision analysis, no prior research was found for assessing the political viability of alternatives. This work theorizes and tests a novel methodology for vote forecasting using the results of a multi-objective decision analysis and comparing alternatives against the status quo. A model scenario is set forth of Customs and Border Protection submitting a funding request for additional technologies to secure the United States-Mexico border. The funding request is sent to a voting body of 20 decision makers from 2 different political parties. A total of 20 funding proposal alternatives are assessed according to the individual preferences of 20 decision makers and votes are forecasted using the results. The experiment with the model scenario made a clear distinction between alternatives with higher and lower levels of political viability. The study contributes a repeatable methodology that can be used for future research in real-life scenarios.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Lt Col Marcelo Zawadzki, for his guidance and support throughout the course of this thesis effort. His insight and experience are greatly appreciated. I would also like to thank my wife for her continued support through the course of my research.

Connor G. Crandall

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Chapter 1: Introduction

1.1 Background

In December 2018, the United States government began the longest shutdown in its history [1]. The reason for the shutdown was an inability of decision makers to come to an agreement about federal spending for a border wall between the United States and Mexico [2]. This event highlighted an interesting decision problem seldomly considered in previous research. Here we have Customs and Border Protection (CBP), acting as a decision maker, submitting funding proposals to congress [3]. However, when it comes to the decision-making process to enact a solution, CBP no longer acts as a decision maker, as their funding is decided by a separate voting body. Beyond this, to a certain extent, CBP is not able to decide where and how the money should be spent once it is received [4]. Thus, it becomes necessary for CBP to not only consider their own priorities and objectives when generating these funding proposals, but to also consider the political viability of any proposal submitted. This is not a problem unique to CBP, all government departments go through similar processes as they request funding and budgets are set by the federal government [5], [6].

1.2 Research Problem

This research proposes using decision analysis techniques to address this problem. Decision analysis is a broad area of study. It is applied to decision problems which, in most cases, contain 5 inherent elements. First, there is a perceived need to accomplish some goal or objective. Second, there are multiple potential solutions, otherwise known as alternatives. Third, each alternative is associated with different consequences. Fourth, there is some amount of uncertainty about the consequences that will follow each alternative. And finally, potential consequences are not considered equal in importance or value [7]. All 5 elements are apparent in the border security problem used for the experiment.

1. Goals and objectives: The United States must adopt some border enforcement strategy, even if that strategy is no enforcement at all. This requirement stems from Article 4, Sec 4 of the U.S. Constitution requiring the federal government to protect states against invasion [8].
2. Multiple potential solutions: There are multiple proposed methods to address border security, including physical and virtual barriers [9], [10], sensors [11], increasing the number of agents [12], along with many other direct and indirect methods [13].
3. Multiple different consequences: Each of the proposed methods have a myriad of consequences tied to them such as costs [14], political popularity [15], expected increases or decreases in apprehensions and drug seizures [16], etc.
4. Uncertainty: Uncertainty is a common element of the border security problem. Many government sponsored systems have much higher than projected costs [17], [18], and many end up having their lifespan extended beyond the initial anticipated window, [17], [19]. Beyond the system itself, there are uncertainties with the DMs responsible for voting on whether or not a particular solution is adopted [20]–[22].
5. Unequal Consequences: With so many decision makers being part of the voting body, there are vastly different priorities regarding what should and should not be valued in terms of consequences [23]–[25].

Pertaining to the issue we are exploring in this work, there are hundreds of decision makers and a near infinite number of potential stakeholders among CBP, other government agencies, and the American public. Beyond this, each decision maker in the voting body has his or her own goals and objectives as it relates to the issue of border security. Finally, decision makers in the voting body are not in the organization tasked with implementing the adopted solution. As a result, factors that might otherwise be irrelevant to the decision problem become intertwined as an effect of the political process. This reality makes the border security problem even more complex and challenging.

1.3 Research Objective and Question

To address this problem, decision makers, like CBP, need a repeatable process that can be used to account for the political viability of the solution before submitting it to the voting body. Therefore, the objective of this research is to theorize and test such a process. This research will explore multi-objective decision analysis techniques and expand them such that they can be utilized to predict the political viability of an alternative. To address this objective, this research sought to answer one investigative research question.

1. How can an analytical framework be used to predict results from voting bodies when assessing multiple alternatives?”

1.4 Methodology

This effort answers the research question by proposing a novel methodology to forecast votes of decision makers (DMs) in a voting body for multiple alternatives by utilizing multi-objective decision analysis techniques. These techniques include constructing a valid value hierarchy to reflect decision makers’ objectives, define attributes, develop single attribute value functions (SAVFs), assess tradeoffs, and aggregate individual scores into an overall value for each alternative reflecting the individual preferences of each DM. Votes are determined by comparing the value scores of every alternative against that of a status quo alternative. More preferred alternatives receive a vote in favor and less preferred alternatives receive a vote against from the respective DM. Vote totals are then used to assess the political viability of alternatives.

With this framework, it is possible to perform multiple informative analyses. We assert that these analyses are good enough for the DM submitting a proposal to a voting body to build adequate situational awareness as to how well or poorly the proposal will be accepted by voters.

1.5 Limitations

As a commissioned military officer, the author of this research is subject to Uniform Code of Military Justice (UCMJ) legal limitations. Article 88 of UCMJ states, "Any commissioned officer who uses contemptuous words against the President, the Vice President, Congress, the Secretary of Defense, the Secretary of a military department, the Secretary of Homeland Security, or the Governor or legislature of any State, Commonwealth, or possession in which he is on duty or present shall be punished as a court-martial may direct" [26]. In keeping with this statute and to maintain the apolitical objective of the research, the author did not attempt to contact any members United States Congress nor CBP officials, whom would be the decision makers in the border security experiment. Instead, all decision maker information was collected from publicly available sources and/or simulated for the experiment.

1.6 Assumptions

No specific assumptions were necessary to generate the model used for the experiment. However, several key assumptions are necessary to apply the novel vote forecasting methodology to any decision problem. Those assumptions are as follows.

1. All decision makers in the voting body have a working knowledge of the issue under consideration such that they are able to provide reliable input data about their personal preferences [27].
2. Decision makers base votes solely on whether they, according to personal preferences, prefer an alternative over the current situation, or status quo. No votes in favor of a proposal are denied out of being good but "not doing enough," spitefulness

or disdain for another decision maker or an opposing political party, nor are any votes in favor of a proposal given out of political favor to another decision maker in the voting body [21].

1.7 Review of Chapters/Research Approach

The remainder of this thesis is comprised of a literature review, explanation of the methodology, the experiment with the results and analysis, and conclusion. The literature review contains a brief overview of the United States legislative process and past government shutdowns, a history on the United States-Mexico border and United States Border Patrol (USBP), and a breakdown of decision analysis (DA) principles. The breakdown identifies types of decision problems and various approaches to solve them. It structures components of DA in such a way as to identify where this research on voting bodies falls among the current body of knowledge. The next chapter explains the methodology used for this research beginning with constructing valid value hierarchies to reflect decision maker objectives and turning them into operational frameworks by determining attributes, defining single attribute value functions (SAVFs), assessing tradeoffs, and aggregating scores to determine an overall value for an alternative. Finally, the methodology describes the novel process for forecasting votes for each of the decision makers. After the methodology, the next chapter details the experiment. This begins by detailing the decision scenario of CBP submitting a funding proposal to a simulated voting body. The remainder of the chapter consists of applications of the methodology to assess the border security problem and determine if the framework can be used to assess political viability of alternatives. It includes an analysis of experiment results and conclusions about the vote forecasting methodology. Finally, chapter 5 discusses conclusions about the research, details limitations and assumptions, and identifies areas of future research.

Chapter 2: Literature Review

2.1 Introduction

This chapter reviews government reports, news articles, and scholarly publications to provide a brief overview about the process for the United States Congress to pass the annual appropriations bill and highlights issues that have led to previous bills not being passed prior to a government shutdown in previous Congressional sessions. It discusses the history of government shutdowns, with further explanation of the 2018-2019 partial government shutdown that spanned 35 days. It gives a short history of United States immigration laws and the United States Border Patrol (USBP) from its foundation to its current home as an agency within Customs and Border Protection (CBP) under command of the Department of Homeland Security (DHS). It examines border enforcement statistics from 1992 to 2019.

We argue that this background provides a sufficient understanding of the complexity of the process that exists between the time a funding solution is proposed and the time the decision makers come to an agreement for the solution to pass in a vote. We also argue that this background is strong enough to provide a complete understanding that, in addition to the process, the issue itself is layered in complexity such that there is no clear structure or solution.

This research dives into the realm of DA in an attempt to propose a model to deal with such complex problems. In this chapter, we review different problem types as well as techniques for structuring and solving complex problems and characterizes the unique area of DA specific to problems decided by voting bodies, which based on the research have received little academic attention.

2.2 The Legislative Process and Government Shutdowns

On December 22nd, 2018, the United States Federal Government began what would become the longest government shutdown in the nation's history [1], [28]. The shutdown resulted from Congress failing to pass an appropriations bill or stopgap spending bill (otherwise known as a continuing resolution or CR) prior to the expiration of a previous CR signed 4 weeks prior. This was the third shutdown of the Trump administration and the twenty-first shutdown since 1976, when the modern congressional budgeting process took effect [2]. Table 1 shows each of the 21 shutdowns since 1976 along with a brief summary as published by the Congressional Review Service [2], [29].

Table 1: Government Shutdowns 1976-2019 [2], [29]

Start date	How many full days?	Over what issue(s)?	How big of a shutdown?	White House led by a	House controlled by	Senate controlled by	Ended with
Dec. 22, 2018	35	$5 billion in funding for a proposed border wall	Significant partial shutdown. 25 Percent of government was closed, 800,000 federal workers missed a month of pay.	Republican (Trump)	Republicans (until Jan. 3) Democrats (since Jan. 3)	Republicans	Short-term funding bill
Feb. 9, 2018	0 (it was 9 hours)	Deficit spending and recent tax cuts	Technical funding gap only	Republican (Trump)	Republicans	Republicans	Short-term funding bill
Jan. 20, 2018	2	Immigration, DACA specifically	Shutdown but with limited effect, occurring mostly over a weekend.	Republican (Trump)	Republicans	Republicans	Short-term funding bill
Oct. 1, 2013	16	Affordable Care Act	Significant shutdown	Democratic (Obama)	Republicans	Democrats	Short-term funding bill and short-term lifting of the debt ceiling
Dec. 15, 1995	21	Range of issues: Medicare, possible balanced budget law, size and scope of government	Significant shutdown	Democratic (Clinton)	Republicans	Republicans	Short-term funding bills
Nov. 13, 1995	5	Range of issues: Medicare, possible balanced budget law, size and scope of government	Significant shutdown	Democratic (Clinton)	Republicans	Republicans	Short-term funding bill
Oct. 5, 1990	3	The deficit	Shutdown with limited effect, occurring over Columbus Day weekend	Republican (George H.W. Bush)	Democrats	Democrats	Short-term funding bill
Dec. 18, 1987	1	Nicaragua, Medicare spending and rules for broadcasters	Technical funding gap only	Republican (Reagan)	Democrats	Democrats	Short-term funding bill
Oct. 16, 1986	1	Spending cuts, military equipment, and the death penalty in drug cases	Workers furloughed a half-day	Republican (Reagan)	Democrats	Republicans	Full-year funding bill and raising of debt ceiling
Oct. 3, 1984	1	Slew of issues: water programs, Nicaragua, defense	Workers furloughed a half-day	Republican (Reagan)	Democrats	Republicans	Full-year spending agreement and federal crime package
Sept. 30, 1984	2	Slew of issues: water programs, Nicaragua, defense	Technical funding gap only	Republican (Reagan)	Democrats	Republicans	Short-term funding bill
Nov. 10, 1983	3	Defense spending, foreign aid, dairy policy and education funding	Technical funding gap only	Republican (Reagan)	Democrats	Republicans	Full-year spending agreement and appropriations bills
Dec. 17, 1982	3	Two missile programs and a jobs programs	Technical funding gap only. Federal workers were told to work as normal	Republican (Reagan)	Democrats	Republicans	Full-year spending agreement
Sept. 30, 1982	1	Hobnobbing. A White House barbecue and Democratic fundraiser delayed processing of the short-term deal	Technical funding gap only. Federal workers were told to work as normal	Republican (Reagan)	Democrats	Republicans	Short-term funding bill
Nov. 20, 1981	2	Spending cuts	Limited effect, occurring over a holiday weekend. The first modern shutdown. Reagan ordered non-essential federal employees to go home	Republican (Reagan)	Democrats	Republicans	Short-term funding bill
Sept. 30, 1979	11	Pay raises for congressional staff and abortion	Technical funding gap, no shutdown. Some Pentagon workers got a few days' worth of half pay	Democrat (Carter)	Democrats	Democrats	Short-term funding bill
Sept. 30, 1978	18	Abortion and defense spending	Technical funding gap, no actual shutdown	Democrat (Carter)	Democrats	Democrats	Short-term funding bill
Nov. 30, 1977	8	Abortion	Technical funding gap, no actual shutdown	Democrat (Carter)	Democrats	Democrats	Short-term funding bill and agreement to let Medicaid fund abortions for rape and incest victims
Oct. 31, 1977	8	Abortion	Technical funding gap, no actual shutdown	Democrat (Carter)	Democrats	Democrats	Short-term funding bill
Sept. 30, 1977	12	Abortion. House and Senate divided over whether Mediaid should fund abortions in cases of rape or incest	Technical funding gap, no actual shutdown	Democrat (Carter)	Democrats	Democrats	Short-term funding bill
Sept. 30, 1976	10	Spending	Technical funding gap, no actual shutdown	Republican (Ford)	Democrats	Democrats	Congress overrode Ford's veto

An appropriations bill or a CR goes through the same process as any other bill that is passed by Congress. A bill must first have one or more sponsors. Once a bill is sponsored, it is assigned to a committee. The committee studies the issue and adjusts the bill as necessary, whereupon they release the bill. Once a bill is released by the committee, it is put on the calendar for a vote before the body. When the bill is brought up for a vote, it may be debated and amended. A simple majority is required for the bill to pass (218 of 435 in the House of Representatives and 51 of 100 in the Senate). Once passed, the bill will move to the other congressional chamber, where it is again put through a committee review and calendared for a vote upon release. Again, a simple majority is required for the bill to pass in the second chamber. If there are discrepancies between the bill passed by the House and the bill passed by the Senate, a committee with members of from both chambers will convene to sort out differences. The final bill must again be brought up for a vote in both chambers before proceeding to the President's desk to be signed into law. The President may veto a bill approved by Congress. However, Congress can vote to override a presidential veto and, if approved by a super majority 2/3 vote from each chamber, the bill will become a law [30], [31]. If Congress fails to complete this process with an appropriations bill or CR by the end of the fiscal year, or when a CR reaches its expiration date, there is a gap in funding and all or portions of the federal government shut down and non-essential employees are furloughed until a bill is signed to restore funding [29].

The Congressional Budget Office estimated that the shutdown that began on 22 December 2018 delayed around $18 billion in federal discretionary spending, reduced real gross domestic product (GDP) by $3 billion during the fourth quarter of 2018 and $8 billion during the first quarter of 2019, totaling $11 billion in GDP lost [32]. According to multiple media sources at the time, along with the Congressional Review Service (CRS) report, border security was the chief issue that prevented Congress from passing an appropriations bill [2], [28], [29], [33]–[35]

2.3 Border Security in Congressional Debate

A concern for border security first manifest itself in 1924. President Coolidge signed the Immigration Act of 1924 (otherwise known as the Johnson-Reed Act), which placed the first numeric restrictions on migrants to the U.S. from other countries [36]. The United States Border Patrol (USBP) was established 2 days later under the Department of Commerce and Labor (DCL) to help enforce the restrictions as well as combat small arms trafficking and alcohol smuggling in the midst of prohibition [37]. Congress passed additional legislation in 1952, with the Immigration and Nationality Act [38] and in 1986 the Immigration Reform and Control Act (IRCA) [39]. Since that time, no comprehensive immigration reform has been passed. Although, the topic of immigration and border security resurged in both congressional and the national debate after the terrorist attacks on September 11, 2001 [37], [40].

While no immigration reform bill has passed Congress since 1986, the Secure Fence Act was passed in 2006. This act authorized and partially funded 700 miles of fencing along the U.S.-Mexico border [41]. The Secure Fence Act is one of the many evidences that the perceived vulnerability of the country was along the United States Southwest border (SWB) rather than the Northern border or coastal regions. In addition, the act evidences the 21st century concern of unlawful entry to the United States between ports of entry [37]. The USBP is the primary enforcement agency for addressing this concern [42].

2.4 Border Patrol History

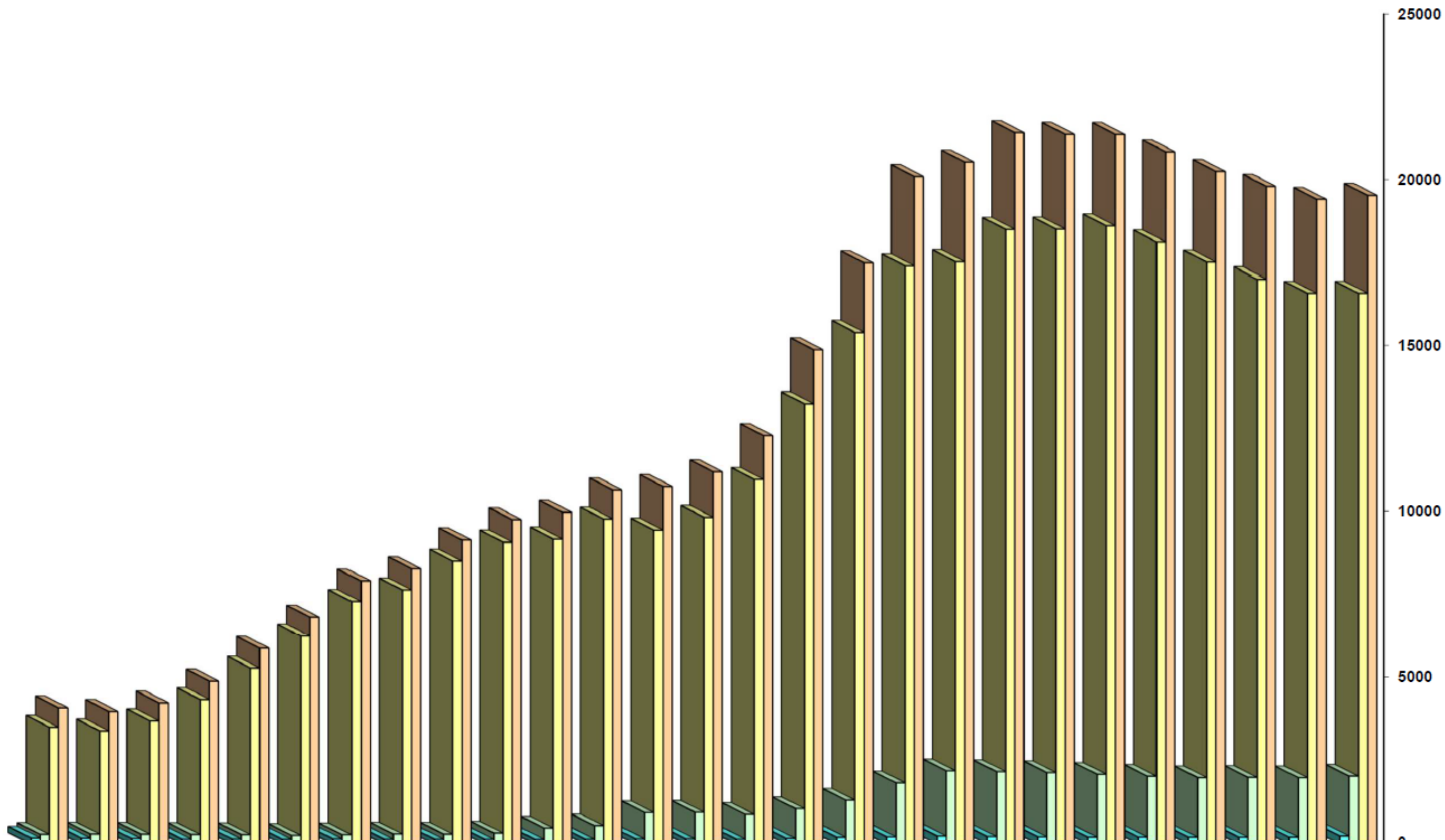
As stated previously, USBP was first established in 1924 under DCL. During this time, most agents were placed at the northern border. In 1933, USBP became part of the newly formed Immigration and Naturalization Service (INS), within DCL. In 1940, the entire INS moved from under DCL to the Department of Justice (DOJ). During World War II (WWII), USBP shifted from the northern border to SWB, but a focus was not placed on preventing illegal migration across the border until the IRCA passed in 1986 [37]. USBP, United States Customs and Border Protection (CBP), the United States Coast Guard (USCG) and Immigration and Customs Enforcement (ICE) share the duty to combat illegal immigration with USBP being primarily responsible for enforcement on U.S. land borders between legal ports of entry. All of these agencies now fall under Department of Homeland Security (DHS), which was established in 2002, in the aftermath of the 9/11 terror attacks in 2001 [43].

2.5 Border Enforcement

Enforcement against illegal immigration has been on an upsurge in the last half-century. Throughout WWII, until 1964, the U.S. and Mexico engaged in the Bracero Program, allowing millions of Mexican workers to legally migrate and work in the United States. During this time, it was common for husbands and sons in Mexican families to migrate to the U.S. to work during planting and harvest seasons and return to their families when the seasonal work ended [44]. USBP did not place an emphasis on halting illegal migration under the Bracero Program, as the constant flow back and forth across the SWB was not seen as a threat to national security. It was the ending of the Bracero Program in 1964 that, in part, triggered the debate that led to the passage of the IRCA in 1986 [37], [44].

Increased enforcement has resulted in an increase in USBP staffing. Figure 1 is a graph depicting the increase in USBP staffing in the SWB, northern, and coastal sectors from 1992-2018. The percentage of agents posted along the SWB has remained constant over time, with an average of 85% of all border patrol agents stationed along the SWB. However, there has been over a 350% increase in the number of SWB agents since 1992. The northern border has seen the largest percent increase, with agents enforcing the northern border rising from about 7% of the nationwide total in 1992 to nearly 11% of the total in 2018. The 4% increase more than a 600% increase in the number of agents assigned to the sector. Coastal border enforcement was the only sector to decrease in percent make-up. Since 1992, coastal border enforcement agents fluctuated between about 150 and 250. This could be due to increased reliance on USCG for coastal border enforcement. In total, USBP staffing increased over 370% between 1992 and 2018 [45].

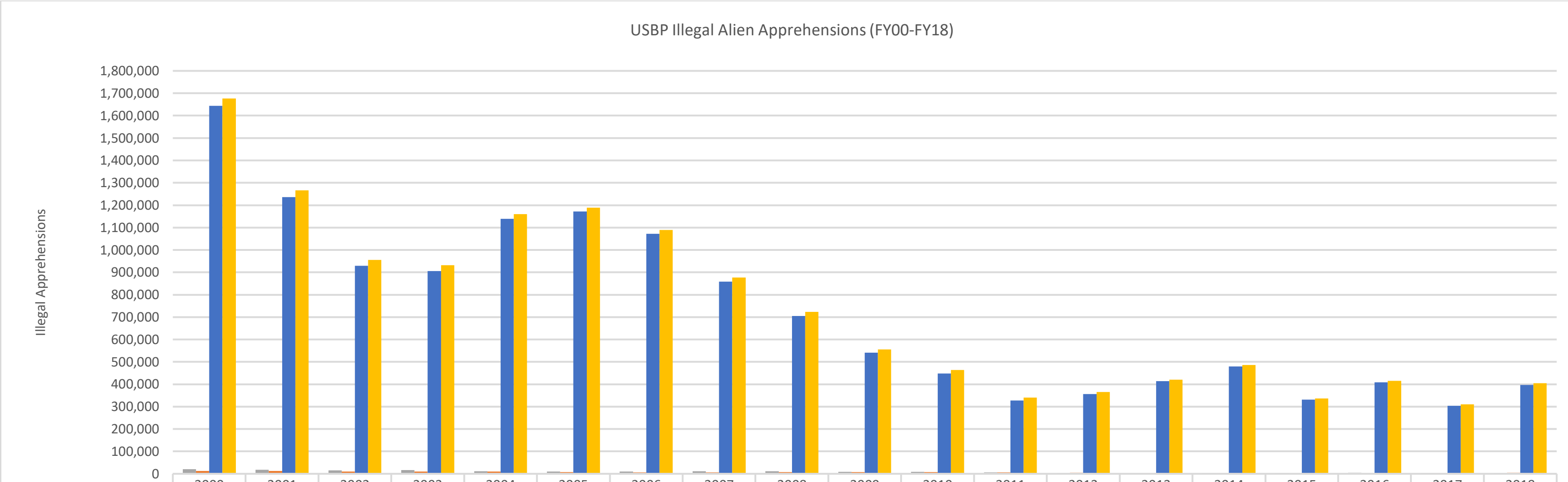
While border staffing has increased, USBP has struggled to effectively whether increased staffing and efforts have led to increased border security. This is due primarily to the fact that there is no defined metric that encapsulates what it means to have a secure border [46]. The National Defense Authorization Act (NDAA) for fiscal year 2017 established 43 metrics for DHS to report [47]. The Government Accountability Office (GAO) later determined only 35 of the 43 metrics were reported, 17 of which contained elements that varied significantly from what was called for by the NDAA [48]. Some of those metrics outlined in the NDAA are the number of apprehensions in each border sector, the number of detected successful unlawful entries (Got Aways), the estimated number of undetected unlawful entries, and the amount and type of illicit drugs seized between ports of entry [47]. Charts summarizing these metrics for USBP are given in figures 2-6.



	FY 1992	FY 1993	FY 1994	FY 1995	FY 1996	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004
Coastal Border Sectors	187	183	170	153	155	146	161	152	150	148	143	152	160
Northern Border Sectors	299	310	306	296	292	267	289	311	306	340	492	569	979
Southwest Border Sectors	3555	3,444	3,747	4,388	5,333	6,315	7,357	7,706	8,580	9,147	9,239	9,840	9,506
Nationwide Totals	4139	4,028	4,287	4,945	5,942	6,895	7,982	8,351	9,212	9,821	10,045	10,717	10,819

	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Coastal Border Sectors	160	153	172	209	223	246	232	224	213	214	212	211	212	248
Northern Border Sectors	988	919	1,098	1,363	1,887	2,263	2,237	2,206	2,156	2,094	2,051	2,059	2,048	2,097
Southwest Border Sectors	9,891	11,032	13,297	15,442	17,408	17,535	18,506	18,516	18,611	18,127	17,522	17,026	16,605	16,608
Nationwide Totals	11,264	12,349	14,923	17,499	20,119	20,558	21,444	21,394	21,391	20,863	20,273	19,828	19,437	19,555

Figure 1: USBP Staffing by Sector (FY92-FY18)[45]



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Coastal Border	20,651	18,158	15,014	16,335	11,154	10,336	10,521	11,686	10,895	8,370	8,220	6,552	3,685	3,162	3,942	3,158	4,663	3,588	3,247
Northern Border	12,108	12,338	10,487	10,157	9,959	7,343	6,599	6,380	7,925	6,806	7,431	6,123	4,210	3,230	3,338	2,626	2,283	3,027	4,316
Southwest Border	1,643,679	1,235,718	929,809	905,065	1,139,282	1,171,396	1,071,972	858,638	705,005	540,865	447,731	327,577	356,873	414,397	479,371	331,333	408,870	303,916	396,579
Total	1,676,438	1,266,214	955,310	931,557	1,160,395	1,189,075	1,089,092	876,704	723,825	556,041	463,382	340,252	364,768	420,789	486,651	337,117	415,816	310,531	404,142

Figure 2: USBP Apprehensions by Sector (FY00-FY18)[16].

Apprehensions between ports of entry (POE) trended downward from FY2000 to FY2018 (see Figure 2). This was true across all 3 border sectors with an 84% reduction across the coastal border, a 64% reduction across the northern border, and a 76% reduction across the Southwest border. Some of the sharpest decreases in apprehension came after increased enforcement efforts following the 9/11 terrorist attacks in 2001, which was accompanied by a brief recession [46], and then again after the passage of the Secure Fence Act of 2006 [41]. Levels fluctuated little between 2010 and 2018, oscillating between 300,000 and 500,000. Despite decreases in total numbers, one metric remained constant throughout the 19-year evaluation, apprehensions along the SWB accounted for over 96% of yearly nationwide illegal alien apprehensions [16].

The metric for Got Aways has only been tracked along the SWB since 2006 (see Figure 3). Since that time, however, USBP has been able to narrow the gap between the estimated total number of successful unlawful entries and the number of detected Got Aways for that sector. That gap is explained by Figure 4, which also shows a decline in the estimate of undetected unlawful entries. Estimated total successful unlawful entries decreased 92% from FY2000 to FY2017 and 83% from FY2006, when detected Got Aways began being recorded. Detected Got Aways decreased 65% from FY2006-FY2017 [49]. According to GAO reports, the methodology for tracking and estimating undetected unlawful entries and, as a result, total successful unlawful entries has only been developed for the SWB [48]. Thus, no sector specific data exists for the other 2 USBP sectors.

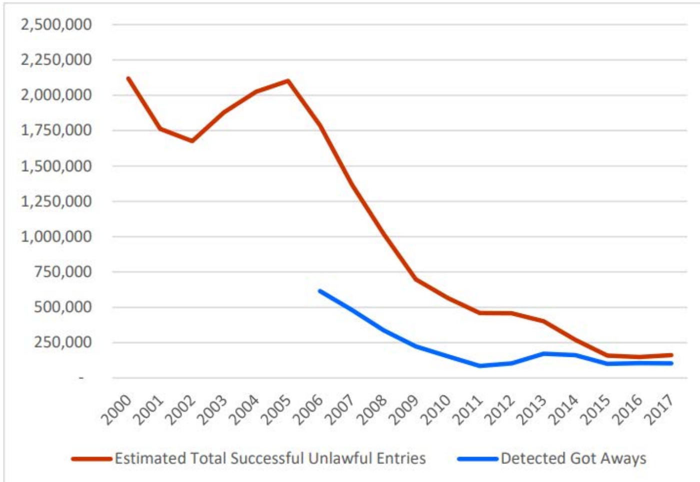


Figure 3: USBP Estimates Total Successful Unlawful Entries and Detected Got Aways between POEs for the SWB [49].

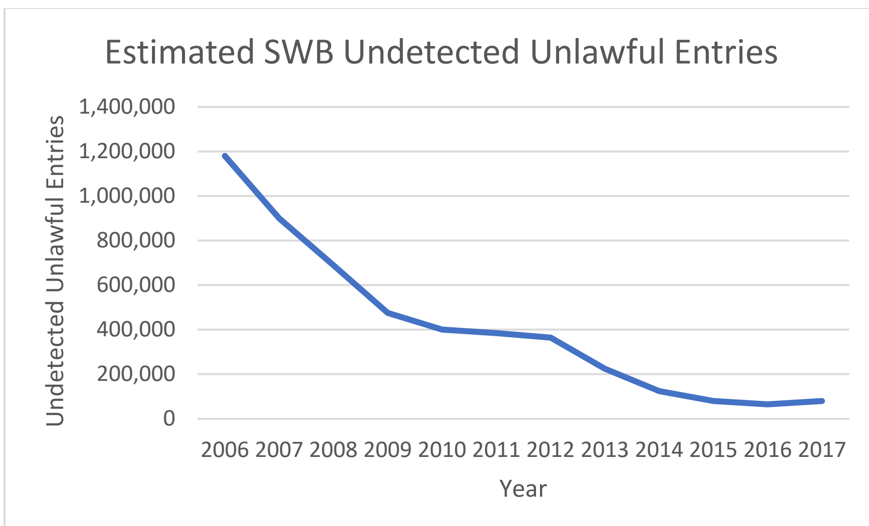


Figure 4: USBP SWB Estimates of Undetected Unlawful Entries. Note: DHS did not publish any data for undetected unlawful entries for either of the other two border sectors [49]*. This is because USBP did not complete a methodology to estimate undetected unlawful entries for the northern or the coastal border sectors* [48].

Drug flow across U.S. borders follows a slightly different pattern than persons attempting to illegally enter the country. Persons illegally crossing into the U.S. do so in response to a myriad of push and pull factors originating from both the United States, and their country of origin [46], [50]. Drugs, on the other hand, like any marketable product, follow the laws of supply and demand [51]. Figure 5 and Figure 6 show the quantities of 5 different illicit drugs seized at and between POEs nationwide. Most hard drugs, meaning drugs that lead physical addiction, are seized by the Office of Field Operations (OFO) at POEs. Between FY2012 and FY2018, the OFO accounted for 86.1% of cocaine seizures, 82.2% of methamphetamine seizures, 88.0% of heroin seizures, and 85.5% of fentanyl seizures. In total, the OFO and USBP seized 388,970 pounds of cocaine, 266,828 pounds of methamphetamine, 35,193 pounds of heroin, and 5000 pounds of fentanyl. Fentanyl, which the OFO and USBP began seizing and tracking in 2015, has seen a consistent increase in the amounts seized since being added to the list of trafficked drugs [51].

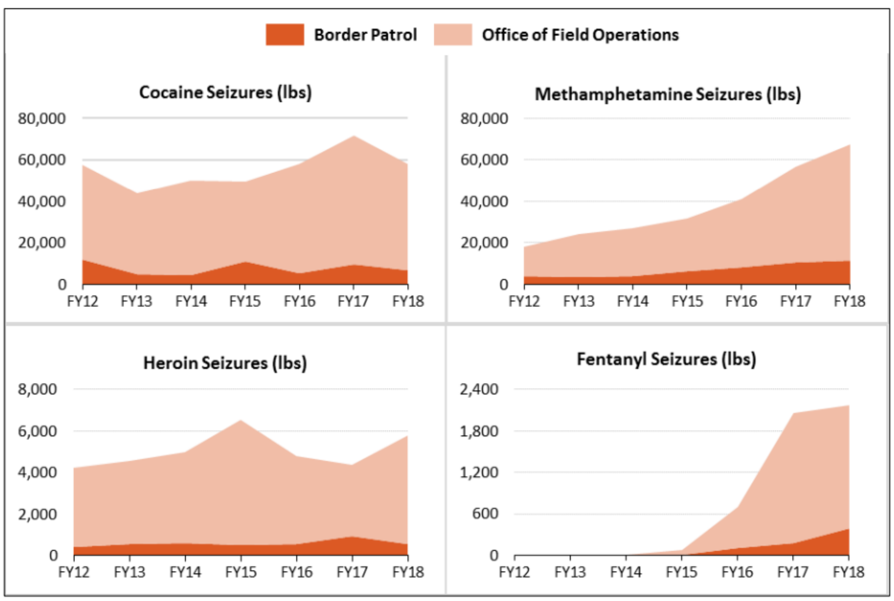


Figure 5: USBP (Between Port of Entry) and Office of Field Operations (At Port of Entry) Illicit Drug Seizures between Ports of Entry (FY12-FY17) [51]

Marijuana is the only drug reported by DHS where most seizures occurred between POEs. It is also the most common pound-for-pound drug trafficked across U.S. borders. From FY2012 to FY2018, the OFO and USBP reported the seizure of 14,023,570 pounds of marijuana with USBP seizing 77.1% of that amount between POEs. The amount of marijuana seized per year decreased 72.9% from FY2012 to FY2018. The majority of that decrease came from USBP seizures [51].

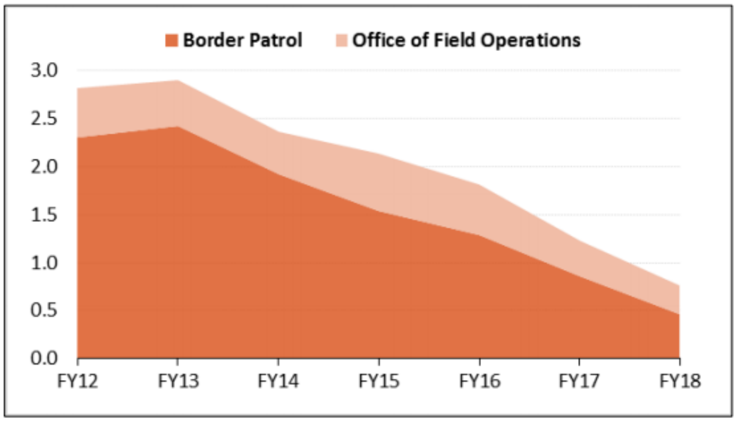


Figure 6: USBP (Between Port of Entry) and Office of Field Operations (At Port of Entry) Marijuana Seizures (FY12-FY18) [51]

Based on these figures alone, a person might assume that the United States is doing a better job of border enforcement. As the number of border agents have increased, the number of apprehensions, Got Aways, and undetected unlawful entries all decreased over the charted time periods. In addition, marijuana, the only drug charted where the majority is trafficked between POEs, has also been on a steady decline up through 2018 [49], [51]. Unfortunately, there is no consensus that decreases in these metrics are valid indications of border security [46]. In fact, 2019 data contradicts this theory.

According to CBP reports, FY2019 ended with the highest number of USBP apprehensions since the passage of the Secure Fence Act in 2006. More than double the FY2018 totals, USBP apprehended 859,501 illegal aliens. An additional 288,523 persons were deemed inadmissible by the OFO when attempting to cross legally at POEs [52]. Over 85% of all those apprehended or deemed inadmissible came across the SWB [53]. Cocaine seizures also saw dramatic upticks in 2019. Both the OFO and USBP nearly doubled the amounts seized from 2018. The OFO seized 89,207 pounds, up 72.9%, and USBP seized 11,682 pounds, up 78.4%. The OFO remained steady on heroin seizures, but USBP saw a 42.2% increase in heroin seizures between POEs. Methamphetamine seizures also rose to their highest levels ever recorded by the OFO and USBP [52]. When this data was analyzed, it created valid concerns about the security of the United States borders, much of which stems from the SWB. These concerns eventually resulted in a partial shutdown of the United States government.

2.6 Border Security Problem Summary

Up to this point in the literature review, we have explained the current concerns of CBP with illegal immigration across the Southwestern border of the United States. With most of the agencies human resources already deployed to the region [45], CBP still struggles to manage the influx of both persons and drugs being illegally trafficked over the SWB [53]. Calls for additional resources, debate in U.S. Congress on funding additional assets for border security in the area led to the longest government shutdown in U.S. history [32]. Based on the information presented thus far, we argue that it would be extremely valuable for CBP to have a way to assess their proposals in terms of political viability prior to submitting them to Congress. This, theoretically, allows them to submit a proposal that, while maybe not their ideal solution, provides more value to CBP than a solution Congress might implement if they were to find a CBP proposal infeasible.

Based on all the points presented and discussed, decision analysis would classify border security as a complex problem. Between the United States House of Representatives and the United States Senate, there are 535 decision makers deliberating over this issue. Official party platforms show differing priorities among decision makers of different parties [54], [55], and public statements from elected officials show variation among decision makers of the same party [56], [57]. Differing goals and objectives among decision makers adds another layer of complexity that makes it inaccurate to label the group as one collective decision maker. Finally, because members of Congress act as the decision makers and not CBP, otherwise irrelevant factors such as the pollical popularity of a decision, other national spending priorities, and official political party position come in and affect decision makers' judgement [58]. Now that the complexity of the border security as a problem has been highlighted, we can apply decision analysis concepts to see how this problem can be structured and assessed.

2.7 Decision Analysis

Decision Analysis is defined by experts as "a philosophy, articulated by a set of logical axioms, and a methodology and collection of systematic procedures, based upon these axioms, for responsibility analyzing the complexities inherent in decision problems." Another, more intuitive definition is, "a formalization of common sense for decision problems which are too complex for informal use of common sense." [7].

Further examination can help classify where, within the broad scope of DA, the border security problem falls. Figure 7 shows a breakdown chart depicting where this author believes the border security problem lies in the DA realm. Following is a brief explanation on the different components of the breakdown chart.

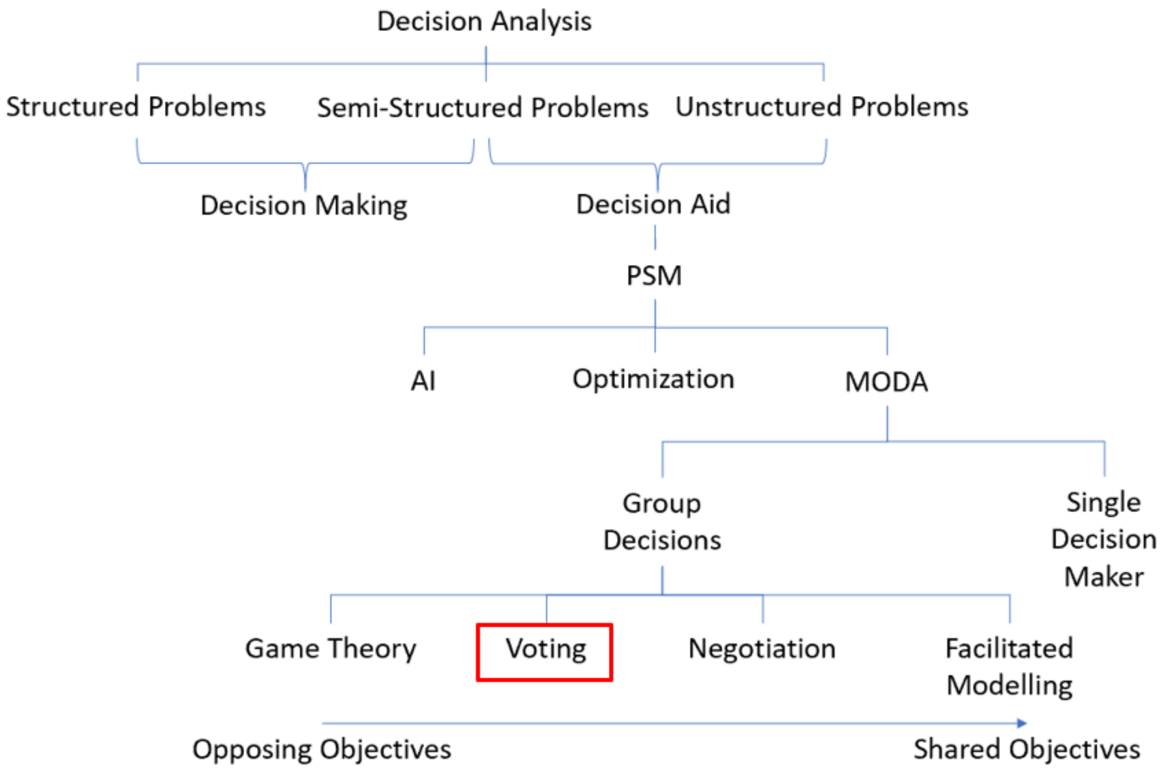


Figure 7: Decision Analysis Breakdown

2.7.1 Problem Structure

The first breakdown in the DA tree separates problems into 3 categories: structured, unstructured, and semi-structured. Structured problems can be thought of as those problems with a clear and concise method for arriving at a solution. For example, a basic investment problem with the objective to maximize profit could be considered a structured problem. Unstructured problems are more complex. These problems do not exist in a vacuum, rather they are affected by external factors and, in turn, have first, second, and even third order effects in terms of the consequences of the decision made. The term semi-structured is not clearly defined and blends boundaries with both structured and unstructured problems. Structured and semi-structured problems typically lend themselves to be solved using computer-based decision support systems (DSS). Unstructured problems, however, require much more research and creativity in order to solve [59].

There are 5 elements that characterize a problem as unstructured: multiple actors, multiple perspectives, incommensurable and/or conflicting interests, important intangibles, and key uncertainties [59]. There is no single computer program that can solve these types of problems [60]. Based on the number of influencing factors and DMs [10], the disconnect between the DMs and the agencies tasked with implementation [42], and the broad effect on the population of the United States at large [61], the border security problem fits well within the category of unstructured problems.

It should also be noted that as problems move along the spectrum of structured to unstructured, problem solving methods can transition from decision making techniques to decision aid techniques. Decision-aid is exactly what the name implies - an aid to assist DMs in the problem-solving process. Results do not claim to deliver the final decision in lieu of the DM; rather, they act as additional inputs for the DM as he, she, or they make the final decision [62]. Given the unstructured nature of the problem, any methodology to address the problem of predicting results of voting bodies best falls under the category of a decision aid rather than a decision-making process. Dealing with unstructured problems relies on utilizing some form of a problem structuring method (PSM).

2.7.2 Solving Unstructured Problems

There is not one method of PSM. Rather, it is comprised of methods that were originally developed independently and differ from traditional mathematical models common to other areas of operations research [59]. These methods are often applied to "wicked" problems that are considered social in nature, not well formulated, have multiple decision makers, and are comprised of confusing information [63]. PSMs are sometimes employed as the sole decision-aid technique for assessing a problem. In these situations, the main goal is to simply gain a better understanding of the issue and not necessarily arrive at any sort of actionable solution. PSM techniques for doing this are more widely accepted in European countries, but have received little attention in the United States [59]. In order to effectively use a PSM, it is best to have direct contact with the decision makers to properly frame the decision space [64]. In some cases, however, it is impossible to establish contact with the decision makers, even though it would be ideal. In these situations, literature can define the reality of the situation to the point that realistic decision maker information can be identified.

There are several areas of study identifying techniques for setting up, and ultimately solving, unstructured problems, of which elements of PSM are sprinkled throughout. Three are mentioned: artificial intelligence (AI), optimization, and multi-objective decision analysis. AI is a rapidly emerging field of study and its uses are becoming more and more mainstream. Types of AI include cognitive engagement, process automation, and cognitive insight. Cognitive engagement and process automation AI are not necessarily intended to solve or aid in complex problems. Cognitive insight AI, however, uses algorithms to identify patterns in large quantities of data and attempts to decipher the meaning. Cognitive insight AI has already been used to deal with complex problems such as identifying credit and insurance claims fraud and identifying safety and quality issues in manufactured goods [65]. As AI continues to progress as a field of study, it may become a candidate methodology to address the complex problem of predicting results of voting bodies.

Optimization is a second technique for solving unstructured problems. Optimization utilizes an objective function, as well as constraint functions, to determine a single best possible solution, or the first solution that does not violate any constraints [66]. This entails defining decision variables and constraints, in addition to defining what “best” means in the given scenario [67]. Optimization can work well for problems with definite objectives, for example, in a situation where the objective is to fit the most powerful engine possible into a vehicle without adding too much weight or cost. This can be inherently difficult, however, when dealing with decision maker objectives because the definition of best becomes more nuanced and can change from decision maker to decision maker. The consequence of different definitions of what is best becomes greater when involving multiple decision makers and grouping them into a voting body. Theoretically, the problem of predicting voting body results could be structured for optimization, but it would ultimately be ineffective. This is because using optimization would account for the baseline issue being voted on, but it would not account for the decision process itself, which is the inherent purpose of this study.

Multi-objective decision analysis (MODA) is the generic term used to describe a decision process that accounts for multiple objectives. MODA has the ability to assess the value or utility of different alternatives by balancing tradeoffs between conflicting objectives [68]. In addition, objectives in a MODA are determined by decision makers, often with the help of analysts [64]. This makes it possible for analyses to be tailored for different decision makers in the problem. Multiple fields of study use MODA for decision aid in complex problems. Some examples include decisions about which crops to plant in different African regions [69] and decisions about how to assess employees in a business while taking into account past achievements, current competencies, and future potential [70]. Elements common to MODA methodologies include overall fundamental objectives, fundamental objectives, fundamental objective specifications, attributes, and weights to assess tradeoffs among objectives [71].

2.7.3 Decision Makers in the Decision Process

This research addresses an aspect of a decision problem not often considered in MODA literature. That is the decision process outside the MODA that must transpire for a solution to be accepted. That decision process is dependent on whether there is one or multiple decision makers for the problem. If there is only one DM in the decision process, it is less complicated because that single DM has sole decision-making authority. In such a situation, analysts need only define the objectives and preferences of that one DM, using whichever preference gathering techniques desired [64]. In reality, however, there is often not a single DM with such authoritarian power. There may be a single approving authority ratifying the final proposal, but that presents a different dynamic than a sole decision maker. Many complex decisions have several DMs involved in the decision process [59], [62]. When multiple DMs are part of the decision process, it is called a group decision [72], [73].

Groups can take many forms. As mentioned previously, a group decision may be a team developing a proposal to submit to the final ratifying authority. It may also be the executive board of a corporation making decisions that impact the company at lower levels as well as the employees. It may be a collection of elected officials establishing laws or budgets for their constituents. Regardless of the group composition, how those groups agree or disagree on the objectives is what further segregates problems into different classifications of DA.

2.7.4 Group Decision Objectives

Groups may be composed of DMs with shared or conflicting objectives. If a group of DMs have a common goal, without reason to benefit one DM over another, the group likely has shared objectives. A MODA study where the goal was to identify the best locations to place temporary relief distribution centers after sudden-onset disasters is an example of a group decision where there were multiple DMs with shared objectives [74]. DMs, despite residing in different locations and serving different populations, all shared a common purpose and were thus seeking ways for greater collaboration rather than gaining advantage over one another. Conversely, in group decisions with conflicting objectives, differences of opinion among DMs is consequential to the final solution. An example could be the buyout of one company by another where the board of the acquiring company must reconcile disagreements with the board of the other company [75].

2.7.5 Addressing Conflicting and Shared Objectives Among DMs

As complex problems move along the scale of DMs with conflicting objectives to having shared objectives, different areas of study are used to assess them. The three areas of study are game theory, negotiation, and facilitated modelling. Studies in each of these areas have used MODA techniques to address political problems with multiple DMs.

Game theory provides an analytical framework to study competition and cooperation [76]. Noncooperative game theory models consist of multiple decision makers, whose objectives are in complete or partial disagreement with one another [77]. A recent study used game theory to assess the effects of social media use by governments to build public support for foreign policy. The study is somewhat similar to the border security problem, in that seeks to determine which policies approved by DMs on a domestic level would also be approved by DMs with different objectives on the global level [78]. Such a framework could be applied in a different study to assess the border security problem.

Another area of study addressing group decisions where DMs have some degree of conflicting objectives is negotiation. Negotiation is a topic that is studied as part of multiple fields including psychology [79], business management [80], and political science [81], in addition to DA. Negotiation is considered to have more common objectives among DMs than game theory models because the very willingness of two or more DMs to negotiate means there is some common objective toward which they are striving. Multiple studies have attempted to formalize negotiation processes using software-based decision support systems (DSS) [72], [82]. A DSS developed in a recent study (hereafter Equalizer) accounts for several DMs with conflicting objectives and attempts to find a balanced solution among the different proposals generated. Equalizer did not rely on alternatives developed ahead of time, but rather assisted each DM, through digital interface, to develop his or her own ideal solution. Then, through a series of iterative steps, helps DMs identify areas where they are willing to compromise until a collective, balanced solution makes itself apparent [72]. In a different study, it may be of interest to assess the border security problem as a group decision using the Equalizer software.

Group decisions with shared objectives lend themselves to facilitated modelling (FM) practices for gathering preference data. FM is an intervention tool where analysts work through every step of problem with the client(s). This includes defining and scoping the problem, identifying stakeholder priorities and helping set plans for solution implementation [83]. A recent study proposed using facilitated modelling approaches for political decisions to enable robust analysis of decisions to assess the rationality of decisions [84].

2.8 Where We Find Ourselves

Decision problems like that of CBP addressing border security present interesting circumstances for problem evaluation. In one sense, CBP is acting as the DM as they decide which funding proposal they will push forward to Congress. At the same time, however, CBP is not really a DM in the decision problem, because the proposal sent forth is merely a recommendation to be considered by Congress. This problem is not unique to CBP. This problem existing anytime a DM is tasked with submitting a proposal to a voting body for approval. It is of interest to DMs submitting proposals that those proposals best serve their own interests and objectives, but if the proposal is not politically viable, it is of much less value for both the DMs and the voting bodies. Beyond this distinction, within a voting body itself, there is only need for compromise among DMs voting in favor of the proposal under consideration. Making compromises with DMs ultimately voting against the proposal adds no political viability value and it may also detract from the overall value of the proposal for those DMs voting in favor of it. If multiple solutions exist which could theoretically be passed by the voting body, there may be different combinations of DMs whose objectives should be considered. Thus, we concluded that concept of submitting proposals to voting bodies falls between game theory and negotiation in terms of shared objectives.

2.9 Conclusion

In the limited scope of this effort, we found little research discussing decision analysis techniques addressing the political viability of alternatives as well as no techniques capable of considering objectives of only those DMs voting in favor of the proposed solution. In the following chapter we present a novel methodology for assessing decision problems with multiple DMs comprised as a voting body. The methodology is able to assess multiple proposals for their political viability and forces no unnecessary compromises among DMs voting in favor of a proposal.

Chapter 3: Methodology

3.1 Introduction

In this chapter, a methodology for developing an effective multi-objective decision analysis (MODA) model that describes the predictive results of a voting body is laid out. An explanation is provided on how to both construct and gather the information for a valid value hierarchy to represent the most important objectives for decision makers (DMs). These elements include the overall fundamental objective, fundamental objectives, and fundamental objective specifications. This chapter explains how to make the value hierarchy an operational framework by describing techniques to select and define attributes, develop single attribute value functions (SAVFs), assess tradeoffs among objectives, and aggregate scores into a single, overall value for each alternative presented and discussed. Two examples of value hierarchies are given - one for a corporate executive board, and the second, for an appointed military voting commission. Finally, this chapter details a novel technique to forecast votes by assessing alternatives for individual DMs in the voting body. An example of a local city tax policy is applied to demonstrate operationalizing a value hierarchy and forecasting votes for a city council consisting of 7 members.

3.2 The Value Hierarchy

Constructing a valid value hierarchy, like other elements of decision analysis (DA) is a process intended to create value [64]. When possible, it is best to involve the DMs and other stakeholders, such as those directly or indirectly impacted by the final decision through organizational or financial interests [85]. However, circumstances often make direct contact with the DMs or stakeholders with primary knowledge of important information infeasible. In this case, a best practice is to utilize a combination of what literature refers to as the Gold and Silver Standard techniques.

The Gold Standard technique for constructing a value hierarchy relies on identifying "Gold Standard" documents, or documents approved by the DMs pertaining to the issue [64]. These documents include public statements [86], drafted bills [9], and documented agendas [54], [55]. This was determined to be an achievable standard for much of the information needed for the hierarchy. Where "Gold Standard" documents are not available, the Silver Standard technique can supplement the data. The Silver Standard technique utilizes data from stakeholders, in addition to the data from DMs to construct the value hierarchy [64].

A value hierarchy is comprised of several layers of objectives (see Figure 8). At the top level, there is a single node for the overall fundamental objective [7], [85], [87]. The intent of this objective is to convey the primary goal or decision objective for the problem. Phraseology for the overall fundamental objective may include words like "best," "greatest," or "top." Objectives further down in the hierarchy define exactly what is meant by these words [7], [64]. The objectives in the layer directly below the overall fundamental objective are called fundamental objectives [7], [85]. Fundamental objectives convey those things that create value in the mind of the DM(s). As value may be an abstract concept for people, identifying fundamental objectives highlights what factors were and were not considered in a given analysis [64]. Beneath fundamental objectives in the value hierarchy are fundamental objective specifications [7]. Fundamental objective specifications, however, are the lowest level definitions for what provides value in the mind of the DM(s) and what words such as "best," "greatest," or "top" mean in context of the overall fundamental objective [64].

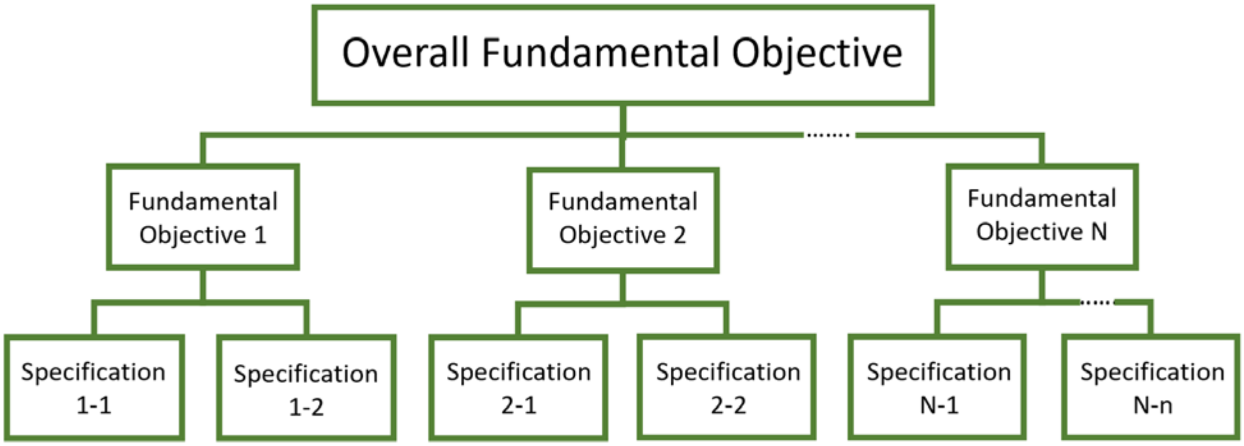


Figure 8: Value Hierarchy Template

To illustrate the construction of a value hierarchy, and demonstrate the versatility of this methodology, two real-world examples are provided of complex decisions that could be presented before a voting body.

3.2.1 <u>The Corporate Example</u>

Drawing from recent news about social media companies, the C.E.O. of Twitter™ recently announced the website would no longer air political advertisements, due to inability to fact check all posted content [88]. Conversely, the C.E.O. of Facebook™ doubled down on the company's hands-off approach and will continue airing the ads on their site [89]. The policy difference demonstrates a decision possibly made by corporate executive boards (i.e. the voting bodies). The DMs in this voting body must account for competing priorities such as profit, public perception, company values, among other things. These competing priorities (objectives) make the issue a prime candidate for MODA and construction of a value hierarchy [62].

Constructing a value hierarchy for this problem requires identifying the 3 levels of objectives. The overall fundamental objective captures the decision objective of the DM(s) for the problem [7], [64]. In this example, the purpose for either of the 2 companies could be the same, "Set the best policy for posting political advertisements on our social media platform." The overall fundamental objective phraseology is meant to be general and all encompassing. It may stem from a vision or mission statement previously agreed upon by the body [64]. The next step is to identify the fundamental objectives or those things that provide value for the DM(s) [7]. For this example they include "Satisfy Customers," "Earn a Profit," and "Maximize adherence to company values" [90]. Each of these fundamental objectives define value in a different way, one through how consumers respond as stakeholders, one addressing monetary value affecting both board members personally and any shareholders of company stock, and the third appealing to the personal ethics or moral value of a solution as interpreted by the board member (i.e. the DM).

To complete the value hierarchy, fundamental objective specifications must be defined to further describe the fundamental objectives and solidify how the word "best" is defined from the overall fundamental objective of the model [7], [64]. The fundamental objective "Satisfy Customers" could be defined with two fundamental objective specifications: "Maximize the number of monthly users" and "Minimize the number of reported advertisements." The fundamental objective "Earn a Profit" could be summarized with the fundamental objective specifications "Maximize Advertisement Earnings" and "Minimize man hours spent reviewing reported advertisements." Finally, the fundamental objective to "Maximize adherence to company values" may need no further specification. This example could be expanded to ensure each fundamental objective is exhaustively defined by the fundamental objective specifications beneath it [91]. However, for purposes of demonstrating construction of a value hierarchy, this was determined to be adequate. Figure 9 shows the constructed value hierarchy for the social media example.

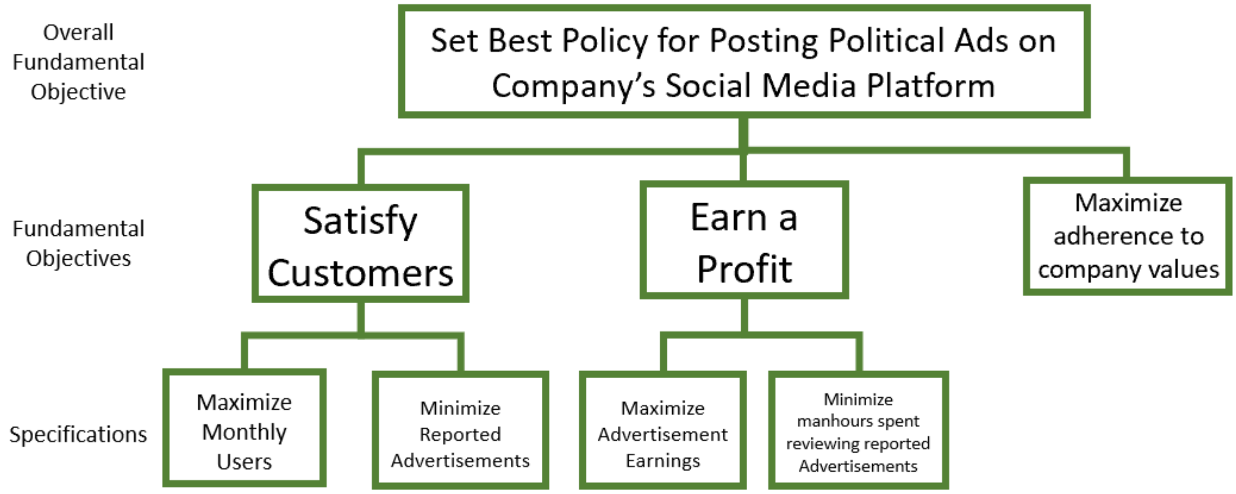


Figure 9: Value Hierarchy-Social Media Example

3.2.2 <u>The Military Example</u>

Voting bodies in the Department of Defense (DoD) are rare, but they do exist. In 2005, President George W. Bush appointed a 9-member commission for the Defense Base Closure and Realignment (hereafter BRAC). The commission (DMs) was tasked to review and analyze all military installations and provide recommendations to improve efficiency through base closure and realignment. They acted as a voting body [92]. The overall fundamental objective could have been similar to the following, "Recommend the best selection for DoD Base Relocation and Closures." Historical documents show the specific criteria (objectives) upon which recommendations were predicated, defining the term "best" in the overall fundamental objective. These fundamental objective specifications were "Maximize Military Value," "Minimize Relocation and Closures Costs," "Maximize Sustainment Cost Savings," "Minimize Economic Impact to the Adjacent Communities," Maximize Repurposing of Infrastructure," and "Minimize Environmental Impact" [92]. This problem is an example of a value hierarchy that requires only an overall fundamental objective and fundamental objective specifications. Figure 10 shows the value hierarchy for this example.

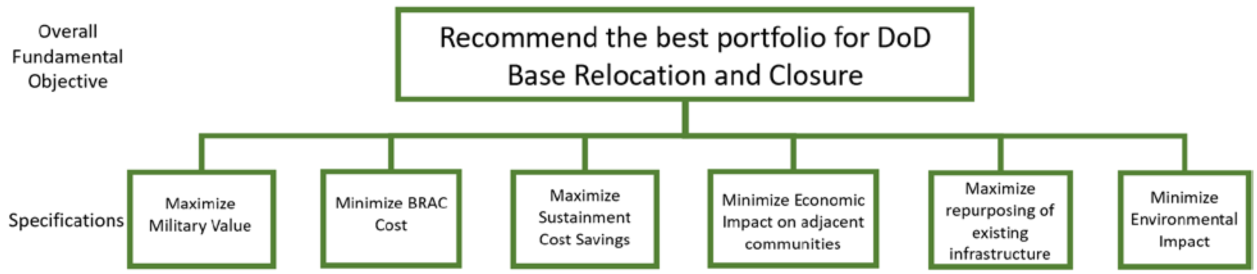


Figure 10: Value Hierarchy-BRAC Example

3.3 Attribute Definition

In order to make the value hierarchy an operational framework for alternatives assessment, each fundamental objective or fundamental objective specification must be associated with an attribute. Attributes further clarify the meaning of the fundamental objectives and specifications in the value hierarchy [91]. Attributes are defined by an evaluation scale, either continuous or discrete. A continuous attribute could be a measure such as cost in $USD, miles per gallon, or percent yield. A discrete attribute is a measure with a finite number of options. Examples include binary attributes such as a Yes/No or a Win/Lose impact level [93].

Beyond the evaluation scale category, there are 2 additional ways to classify attributes. They can be classified by type and alignment (see Table #) [64]. The two types of attributes are natural and constructed. Natural attributes use evaluation scales that are commonly used and generally understood. Constructed attributes use evaluation scales developed for the decision problem. The two alignments of attributes are direct and proxy. Direct attributes clearly and completely measure to what degree the objective has been realized. Proxy attribute use evaluation scales that reflects the degree to which the objective has been realized, but not as clearly nor completely as the direct attribute [68].

Other than clarifying the meaning of the fundamental objectives and specifications, attributes are required to measure the performance of an alternative [91]. In order to measure the performance of an alternative, each attribute is associated with a SAVF [68], [94], [95]. In order to better explain this concept and the remainder of steps in the methodology, we will reference a hypothetical example of a city government seeking to change their local income tax policy.

3.3.1 Attribute Definition-City Tax Example

In cities within the United States, city councils are comprised of 5 to 51 elected members [96]. These councils act as the local government, setting social, legal, and fiscal policy for their jurisdictions. There are cities in 17 states across the U.S. where councils have authority to impose a local income tax on residents [97]. In this hypothetical scenario, a city council of 7 members, governing a city of 125,000 working age people, wants to simplify their city income tax code. Table 2 shows the current income brackets and associated tax rates for the city. Table 3 shows the 3 base alternatives from the council and Table 4 shows the 28 possible alternatives for consideration.

Table 2: Status Quo Alternative-City Tax Example

Income Bracket	<$55,000 per year	$55,000-$125,000 per year	$125,000-$395,000 per year	$395,000-$850,000 per year	>$850,000 per year
Tax Rate	0%	0.5%	1%	1.25%	1.75%

Table 3: Initial Alternatives-City Tax Example

Income Bracket	<$100,000 per year	$100,000-$500,000 per year	>$500,000 per year
Low	0.0%	0.5%	1%
Medium	0.5%	1.25%	2%
High	1.0%	2.0%	3%

Table 4: Alternatives-City Tax Example

Income Bracket	**<$100,000 per year**	**$100,000-$500,000 per year**	**>$500,000 per year**
Alternative 1	0%	0.5%	1%
Alternative 2	0%	0.5%	2%
Alternative 3	0%	0.5%	3%
Alternative 4	0%	1.25%	1%
Alternative 5	0%	1.25%	2%

Alternative 6	0%	1.25%	3%
Alternative 7	0%	2.0%	1%
Alternative 8	0%	2.0%	2%
Alternative 9	0%	2.0%	3%
Alternative 10	0.5%	0.5%	1%
Alternative 11	0.5%	0.5%	2%
Alternative 12	0.5%	0.5%	3%
Alternative 13	0.5%	1.25%	1%
Alternative 14	0.5%	1.25%	2%
Alternative 15	0.5%	1.25%	3%
Alternative 16	0.5%	2.0%	1%
Alternative 17	0.5%	2.0%	2%
Alternative 18	0.5%	2.0%	3%
Alternative 19	1%	0.5%	1%
Alternative 20	1%	0.5%	2%
Alternative 21	1%	0.5%	3%
Alternative 22	1%	1.25%	1%
Alternative 23	1%	1.25%	2%
Alternative 24	1%	1.25%	3%
Alternative 25	1%	2.0%	1%
Alternative 26	1%	2.0%	2%
Alternative 27	1%	2.0%	3%

Income Bracket	**<$55,000**	**$55,000-$125,000**	**$125,000-$395,000**	**$395,000-$850,00**	**>$850,000**
Status Quo	0%	0.50%	1%	1.25%	1.75%

Enlisting an analyst's help, the council developed a basic value hierarchy detailing those things that they perceive as creating value with an overall fundamental objective and fundamental objective fundamental objective specifications (see Figure 11).

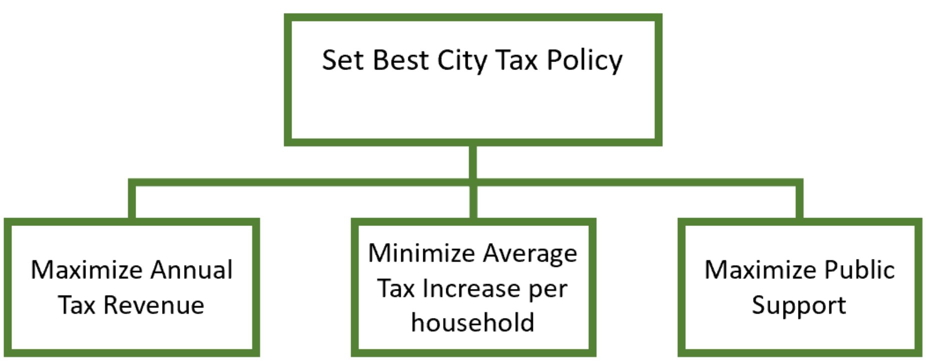


Figure 11: Value Hierarchy-City Tax Example

The first attribute lines up with the first fundamental objective “Maximize Annual Tax Revenue.” Tax revenue is measured in $USD. Thus, the attribute for this fundamental objective is “Tax Revenue in $USD.” This is a continuous attribute. Using $USD as the metric for the evaluation scale directly aligns with the associated objective and it is a natural attribute that is commonly understood. Lastly, for categorization purposes, value for DMs goes up as tax dollars go up as well. This makes it an increasing attribute. The next step to define this attribute is to set the limits. The value with the lowest impact level, or worst value, for “Tax Revenue in $USD” can be set at the logical limit $0. The value with the highest impact level is set at the highest total amount of tax revenue that could be collected based on the rates being considered. Based on preliminary estimates, the highest amount of tax revenue the city expects to collect is $430,300,000. This process could then be repeated for the remaining two fundamental objectives.

The fundamental objective “Minimize Average Tax Increase per Household” is evaluated with the attribute “Tax Increase in $USD per Household.” This attribute is a decreasing function, due to the fact that as value is added for the DMs, the numbers for the evaluation scale go down [68].This attribute is a direct measure, as it wholly captures the objective it seeks to define. However, average $USD per household is a constructed attribute because it is created specifically for this problem [64], [91]. The minimum for the function is the highest possible average tax increase per household, which was estimated to be an increase of $1790 per household annually. The maximum value was estimated to be an average decrease of $730 per household annually, or a -$730 annual increase.

Finally, the fundamental objective “Maximize Public Support” is evaluated with the attribute “Polling Support in Percent.” This attribute is an increasing function and a direct measure as polling results show what the public supports. It is also a natural attribute because a 0%-100% evaluation scale is widely used and commonly understood [64], [91]. The minimum for the attribute with the lowest impact level is 0%. The maximum value for the attribute with the highest impact level is the 100%. Figure 12 shows the value hierarchy with the attributes assigned for each of the 3 fundamental objectives.

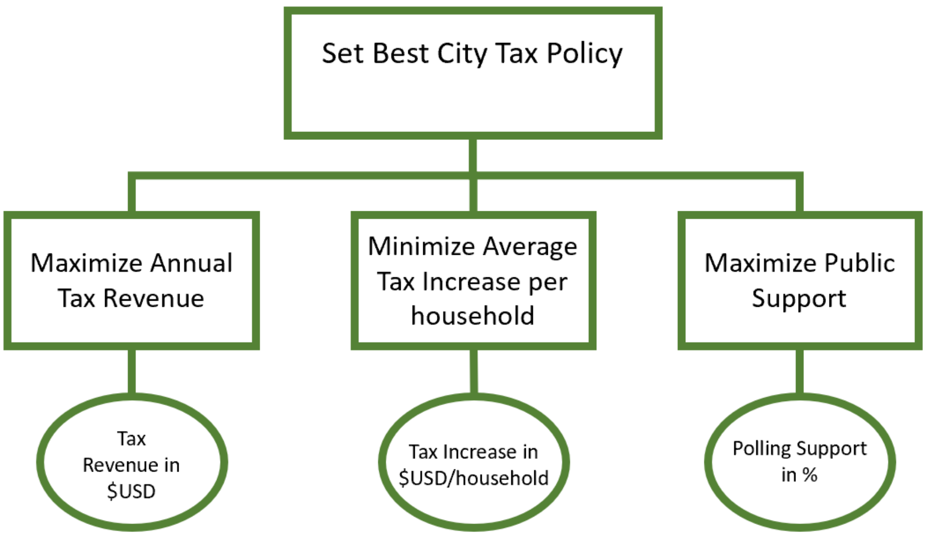


Figure 12: Value Hierarchy with Attributes-City Tax Example

Once attributes are defined for each objective in the hierarchy, the next step is to associate each attribute with a single attribute value function (SAVF).

3.4 Single Attribute Value Functions

Each SAVF quantifies the value of an alternative according to the evaluation scale for the attribute [68], [94]. In most cases, these values are defined in such a way that they fall between 0 and 1. SAVFs can take many shapes including linear, exponential, s-shaped, and stepwise [64], [68]. There are 2 primary ways to elicit the information from DMs to develop SAVFs. The first is the direct rating method, and the second is the bisection method.

The direct rating method consists of DMs giving an exact numeric value score for each scenario [93]. A common technique to gather this information is using surveys with a 5 or 7-point Likert scale.

The bisection method requires 3 parameters, the maximum, minimum, and mid-value for an attribute. The maximum and minimum values are the limits of acceptable values for the DM(s). The word maximum means the number on the attribute's evaluation scale that correlates to the highest impact level, or best value, for the DM. The word minimum refers to the number that correlates to the lowest impact level, or worst value, for the DM [93]. Using the BRAC problem as an example, the minimum value for a cost attribute named "Cost in $", related to the fundamental objective specification "Minimize BRAC Cost," could be around $6.6 billion as the lowest impact level [98]. The maximum for the same attribute could be $0 as the highest impact level, because that is the smallest possible amount that could be spent.

The mid-value is the point between the maximum and minimums where DMs claim to be 50% satisfied [68], [93]. For this methodology, the mid-value is unique to the DM. Continuing with the "Cost in $" attribute for the BRAC example, one DM may claim to be 50% satisfied with a lifecycle cost of $5 billion while another DM may be much more averse to spending and have a mid-value of $2.5 billion. When possible, mid-values should be gathered through direct engagement with the DMs. Mid-values reflect the risk preference of DMs with respect to the given attribute [99].

After establishing the limits and mid-value for an attribute, the next step is to construct the SAVF. For continuous attributes, exponential value functions are generally used. It uses the 3 parameters from the bisection method. Literature shows that the exponential function is sufficient to shape DMs' SAVF to reflect their preferences under most circumstances [100]. The first thing that must be done to construct the SAVF is calculate the normalized mid-value ($z_{0.5}$). The equation to calculate the normalized mid-value is shown in 1.

$$(1) \qquad z_{0.5} = \begin{cases} \dfrac{x_{mid} - x_{low}}{x_{high} - x_{low}}, & when\ increasing \\ \dfrac{x_{high} - x_{mid}}{x_{high} - x_{low}}, & when\ decreasing \end{cases}$$

Where $z_{0.5}$ is the normalized, x_{high} is the upper limit of values possible for the attribute, x_{low} is the lower limit of values possible for the attribute, and x_{mid} is the mid-value derived from the DM. The terms increasing and decreasing refers to the direction of rising value for the DM. With the normalized mid-value ($z_{0.5}$), the normalized exponential constant (R) can be determined using Table 2 [68].

Table 5: Calculating the Normalized Exponential Constant [68]

$z_{0.5}$	R	$z_{0.5}$	R	$z_{0.5}$	R	$z_{0.5}$	R
0.00	—	0.25	0.410	0.50	Infinity	0.75	-0.410
0.01	0.014	0.26	0.435	0.51	-12.497	0.76	-0.387
0.02	0.029	0.27	0.462	0.52	-6.243	0.77	-0.365
0.03	0.043	0.28	0.491	0.53	-4.157	0.78	-0.344
0.04	0.058	0.29	0.522	0.54	-3.112	0.79	-0.324
0.05	0.072	0.30	0.555	0.55	-2.483	0.80	-0.305
0.06	0.087	0.31	0.592	0.56	-2.063	0.81	-0.287
0.07	0.101	0.32	0.632	0.57	-1.762	0.82	-0.269
0.08	0.115	0.33	0.677	0.58	-1.536	0.83	-0.252
0.09	0.130	0.34	0.726	0.59	-1.359	0.84	-0.236
0.10	0.144	0.35	0.782	0.60	-1.216	0.85	-0.220
0.11	0.159	0.36	0.845	0.61	-1.099	0.86	-0.204
0.12	0.174	0.37	0.917	0.62	-1.001	0.87	-0.189
0.13	0.189	0.38	1.001	0.63	-0.917	0.88	-0.174
0.14	0.204	0.39	1.099	0.64	-0.845	0.89	-0.159
0.15	0.220	0.40	1.216	0.65	-0.782	0.90	-0.144
0.16	0.236	0.41	1.359	0.66	-0.726	0.91	-0.130
0.17	0.252	0.42	1.536	0.67	-0.677	0.92	-0.115
0.18	0.269	0.43	1.762	0.68	-0.632	0.93	-0.101
0.19	0.287	0.44	2.063	0.69	-0.592	0.94	-0.087
0.20	0.305	0.45	2.483	0.70	-0.555	0.95	-0.072
0.21	0.324	0.46	3.112	0.71	-0.522	0.96	-0.058
0.22	0.344	0.47	4.157	0.72	-0.491	0.97	-0.043
0.23	0.365	0.48	6.243	0.73	-0.462	0.98	-0.029
0.24	0.387	0.49	12.497	0.74	-0.435	0.99	-0.014

Once the normalized exponential constant (R) has been determined, the exponential constant (ρ) can be calculated. The equation is shown in 2 [68].

$$(2) \qquad \rho = R(x_{high} - x_{low})$$

Finally, with the exponential constant (ρ) and the limits (x_{high}, x_{low}) for the attribute, the SAVF can be generated using either the equation shown in 3, for increasing functions, or the equation shown in 4, for decreasing functions.

$$(3) \qquad v(x,\rho) = \begin{cases} \dfrac{1 - e^{[-(x - x_{low})/\rho]}}{1 - e^{[-(x_{high} - x_{low})/\rho]}}, & when\ \rho \neq Infinity \\ \dfrac{x - x_{low}}{x_{high} - x_{low}}, & otherwise \end{cases}$$

$$(4) \qquad v(x,\rho) = \begin{cases} \dfrac{1 - e^{[-(x_{high} - x)/\rho]}}{1 - e^{[-(x_{high} - x_{low})/\rho]}}, & when\ \rho \neq Infinity \\ \dfrac{x_{high} - x}{x_{high} - x_{low}}, & otherwise \end{cases}$$

Where $v(x,\rho)$ is the single attribute value score, ρ is the exponential constant, x is the variable objective score for the alternative, and (x_{high}, x_{low}) are the limits for the attribute. Because each DM in the voting has his or her own mid-value for each attribute, there will be a unique exponential constant (ρ) for each attribute for each DM. This means that the number of unique SAVFs for this methodology will be equivalent to the number of attributes in the value hierarchy multiplied by the number of DMs in the problem.

3.4.1 SAVFs-City Tax Example

By soliciting DMs directly, the mid-values for the annual tax revenue can be collected for the 7 city councilman in the example. DM responses can be plotted on a numeric scale as seen in Figure 13. The direction of the arrow indicates the direction of increasing value for the DMs.

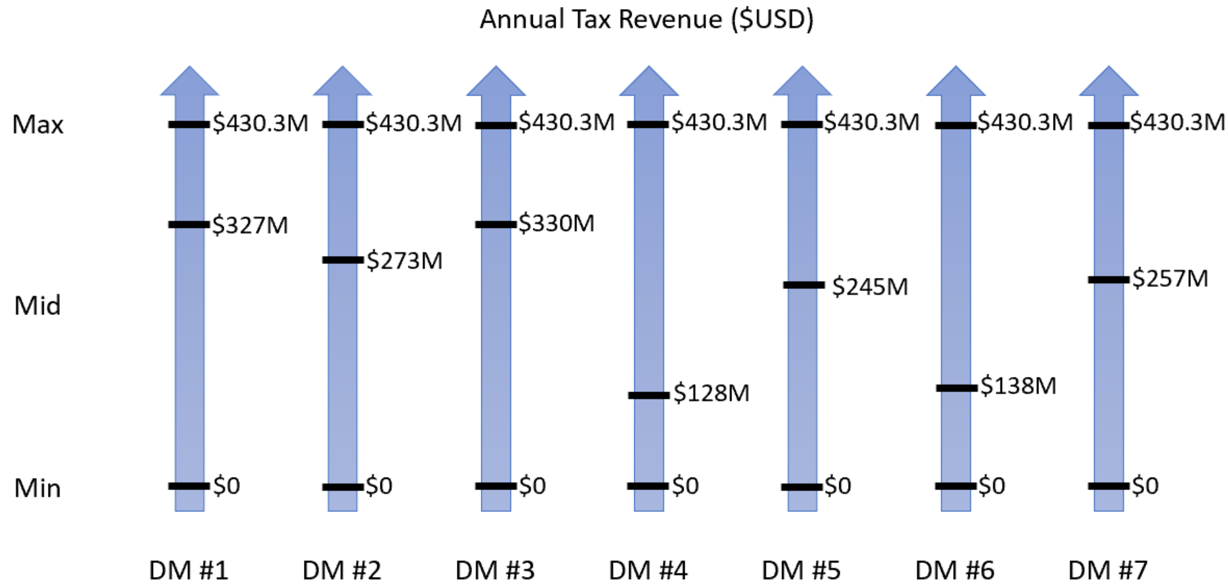


Figure 13: Evaluation Scales for all DMs-Annual Tax Revenue, City Tax Example

The SAVF is determined by first calculating the normalized mid-value ($z_{0.5}$) for each DM using the equation shown in 1. With the normalized mid-value, the normalize exponential constant (R) can be derived using Table 5, and the exponential constant (ρ) can be calculated using the equation shown in 2. Each of these three values are given for each of the 7 DMs in the voting body in Table 6.

Table 6: Mid-Value and Exponential Constants-Annual Tax Revenue, City Tax Example

Annual Tax Revenue ($USD)	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
Mid-Value	$327M	$273M	$330M	$128M	$245M	$138M	$257M
$z_{0.5}$	0.24	0.37	0.23	0.70	0.43	0.68	0.40
R	0.387	0.917	0.365	-0.555	1.762	-0.632	1.216
ρ	166526100	394585100	157059500	-238816500	758188600	-271949600	523244800

Because the function for annual tax revenue attribute is an increasing function, equation 3 can be used to construct the SAVF. Each DM in the voting body will have a unique SAVF for this attribute. Figures 14-20 show the 7 unique SAVFs for this attribute.

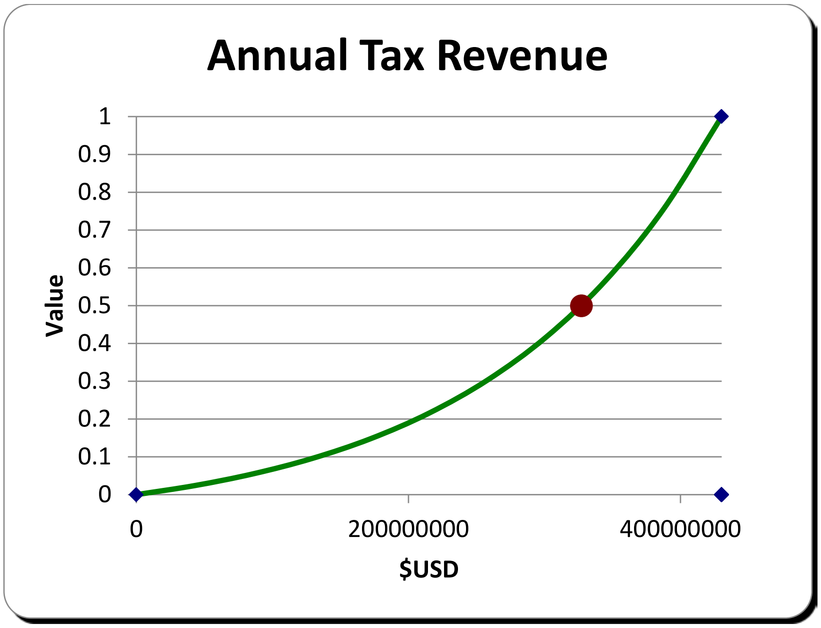


Figure 14: SAVF-Annual Tax Revenue, DM 1, City Tax Example

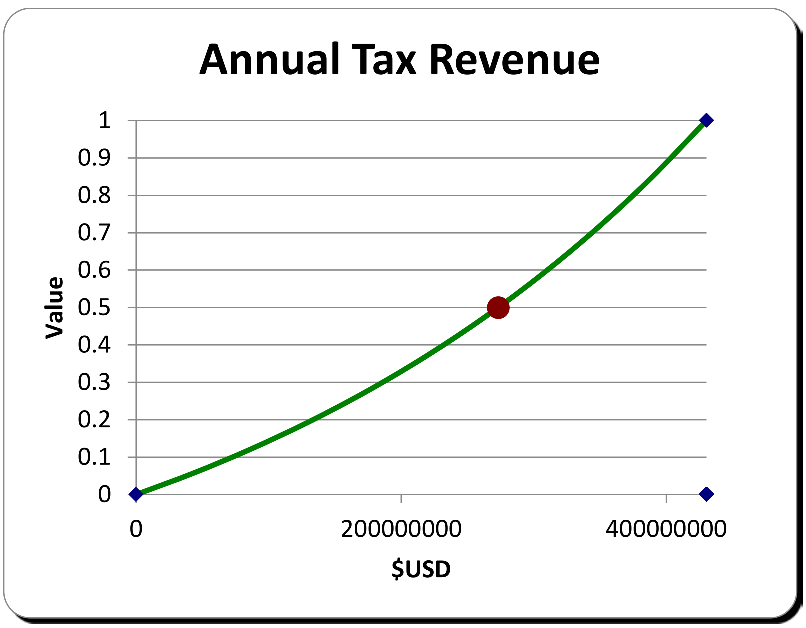


Figure 15: SAVF-Annual Tax Revenue, DM 2, City Tax Example

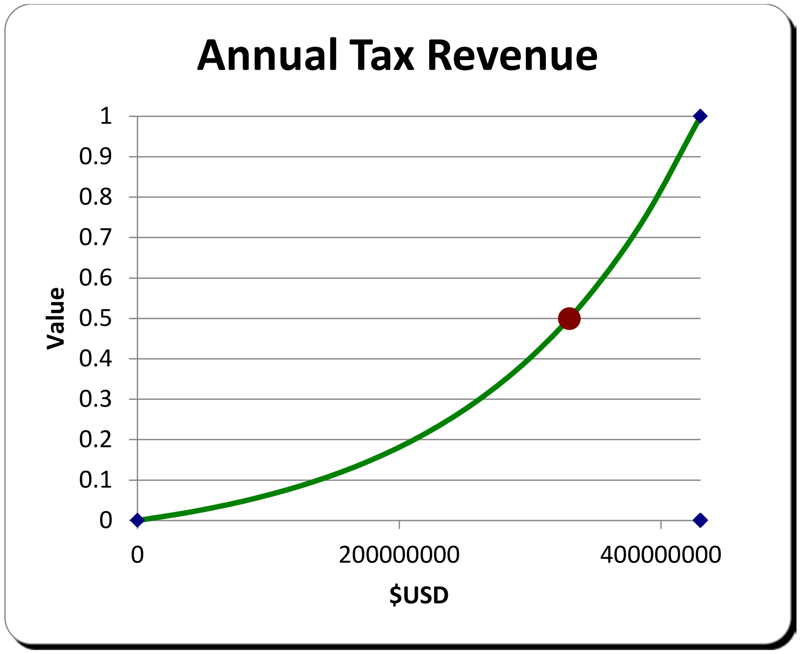


Figure 16: SAVF-Annual Tax Revenue, DM 3, City Tax Example

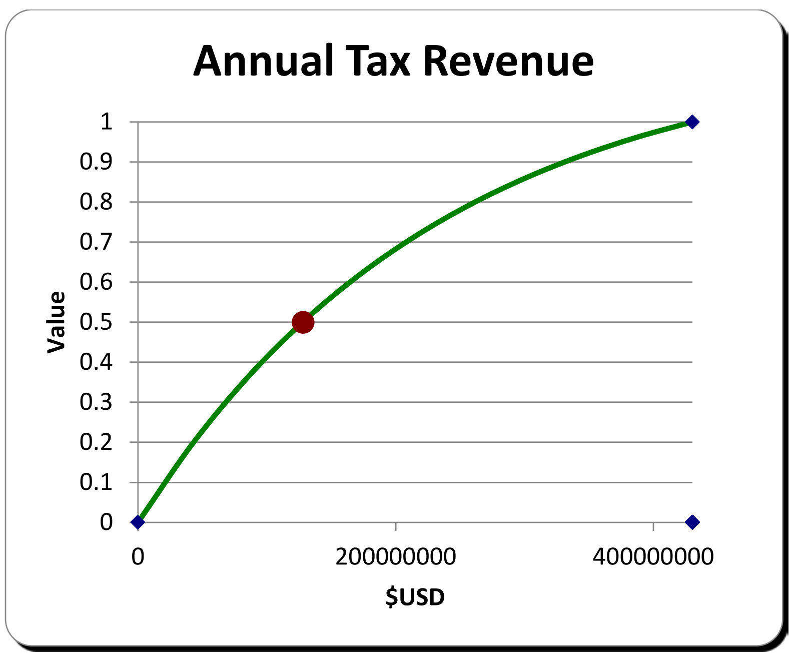


Figure 17: SAVF-Annual Tax Revenue, DM 4, City Tax Example

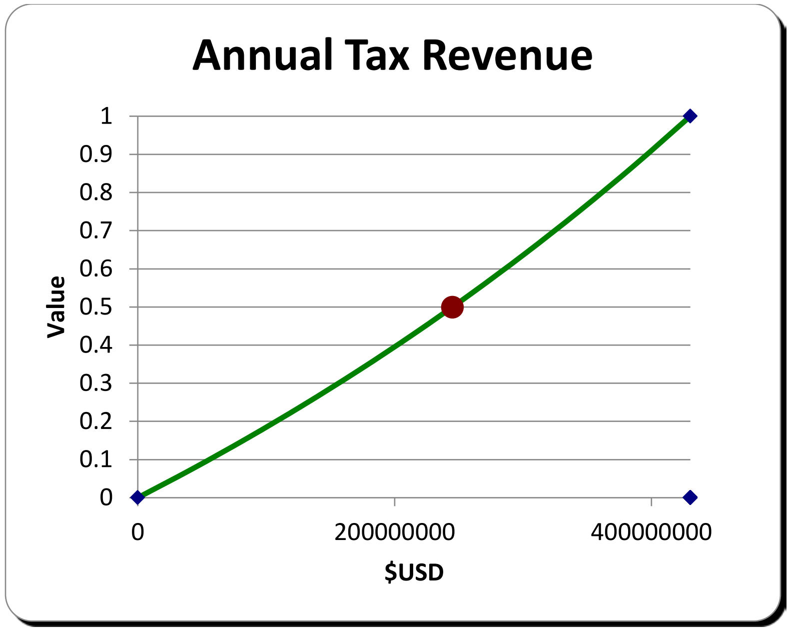


Figure 18: SAVF-Annual Tax Revenue, DM 5, City Tax Example

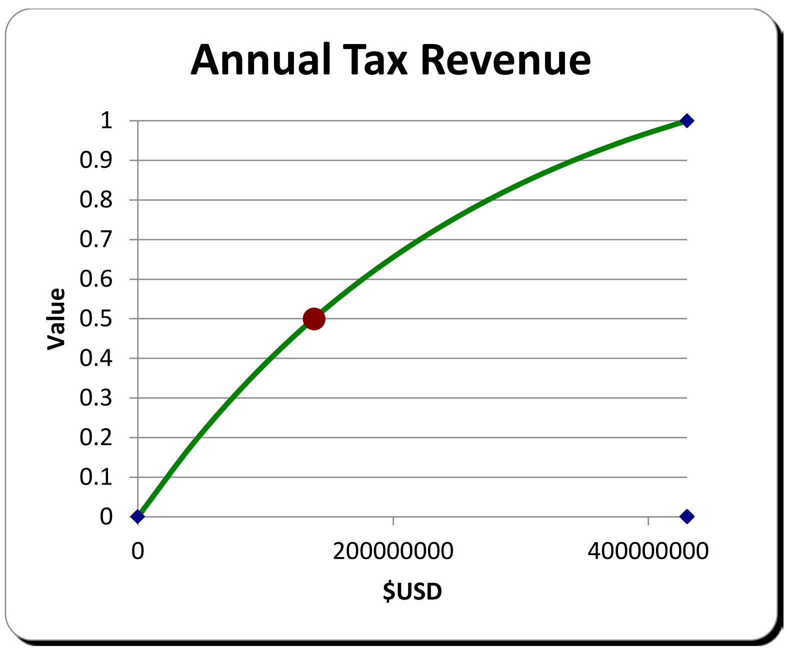


Figure 19: SAVF-Annual Tax Revenue, DM 6, City Tax Example

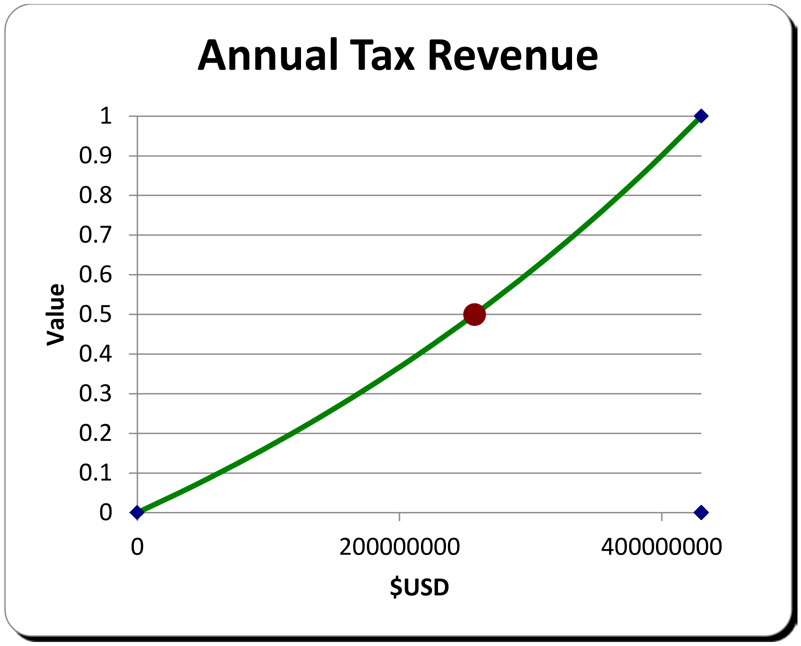


Figure 20: SAVF-Annual Tax Revenue, DM 7, City Tax Example

Figure 21 shows the evaluation scales for the attribute "Tax Increase in $USD per Household" for each DM in the voting body with the limits and mid-values.

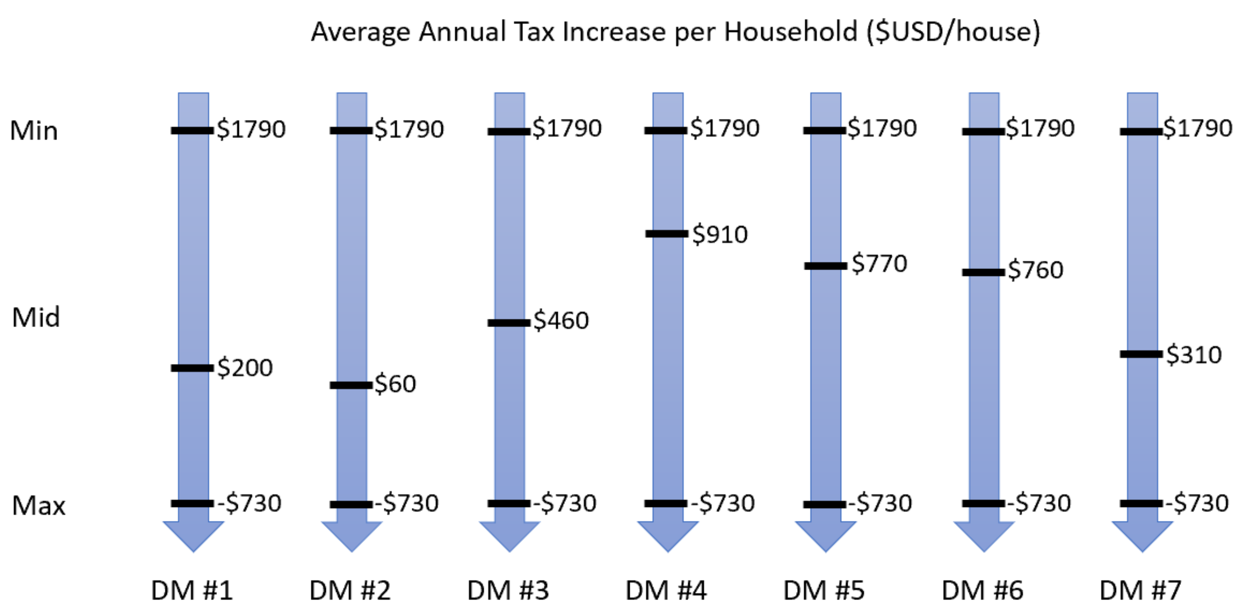


Figure 21: Evaluation Scales for all DMs-Average Annual Tax Increase per Household, City Tax Example

The mid-values, normalized mid-values ($z_{0.5}$), normalized exponential constants (R), and exponential constants (ρ) for all 7 DMs in the voting body are given in Table 7.

Table 7: Mid-Value and Exponential Constants-Average Annual Tax Increase per Household, City Tax Example

Average Tax Increase per household ($USD/house)	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
Mid-Value	$200	$60	$460	$910	$770	$760	$310
$z_{0.5}$	0.37	0.31	0.47	0.65	0.60	0.59	0.41
R	0.917	0.592	4.157	-0.782	-1.216	-1.359	1.359
ρ	2311	1492	10476	-1971	-3064	-3425	3425

The function for the attribute "Tax Increase in $USD per Household" is a decreasing function. As a result, the equation shown in 4, instead of the equation shown in 3, is used to form the SAVF. Similar to the previous attribute (Figures 14-20), 7 unique value functions are derived, representing the 7 DMs value assessment for this attribute.

Figure 22 shows the evaluation scales for each DM in the voting body with the maximum, minimum, and mid-values.

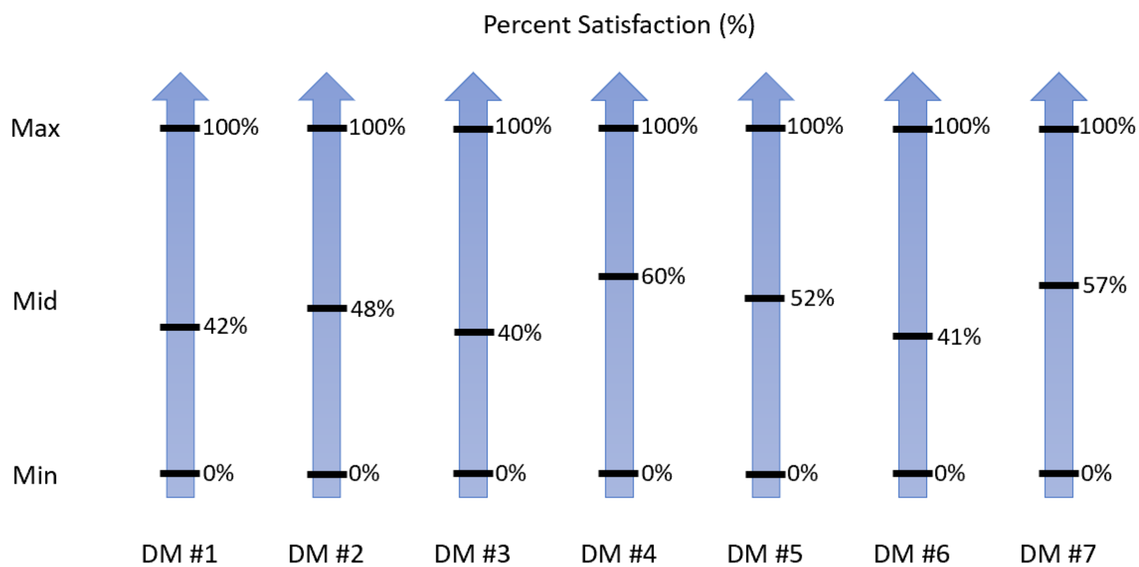


Figure 22: Evaluation Scales for all DMs-Percent Satisfaction, City Tax Example

The mid-values, normalized mid-values ($z_{0.5}$), normalized exponential constants (R), and exponential constants (ρ) for all 7 DMs in the voting body are given in Table 8.

Table 8: Mid-Value and Exponential Constants-Percent Satisfaction, City Tax Example

Percent Satisfaction (%)	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
Mid-Value	42	48	40	60	52	41	57
$z_{0.5}$	0.58	0.52	0.60	0.40	0.48	0.59	0.43
R	-1.536	-6.243	-1.216	1.216	6.243	-1.359	1.762
ρ	-1.563	-6.243	-1.216	1.216	6.243	-1.359	1.762

The function for the attribute “Polling Support in Percent” is an increasing function. Therefore, like the attribute for “Tax Revenue in $USD”, exponential constants (ρ) for each DM, along with the maximum and minimum are used in equation 3 to form the SAVF. In addition, like the attribute for annual tax revenue (Figures 14-20), 7 unique value functions are derived, representing the 7 DMs value assessment for this attribute. At this point, all attributes for the value hierarchy have been defined. The SAVFs for attributes are used to determine a value score for each of the alternatives.

3.5 Objective Scoring for Alternatives

In order to evaluate alternatives using a SAVF, it is necessary to score each alternative’s performance with respect to the attribute. That is done by converting alternatives from the format in which they are given into the metrics used by the attribute. In the case of the Department of Defense BRAC example again, an alternative would be given in the form of base locations closed or relocated. In order to score an alternative for the “Cost in $” attribute, it would be necessary to determine the total cost of closing and relocating all the bases in that alternative. A hypothetical example from a local city government will be used to further convey the ideas of developing attributes and SAVFs.

3.5.1 City Tax Example

The alternatives in this example are given in terms of income brackets and associated tax rates. A separate calculation must be done to convert alternatives into useable metrics in the SAVFs for each attribute. Based on the number of citizens in each income bracket and the average income of all citizens in that income bracket, it is possible to calculate the "Tax Revenue in $USD" for each alternative. By comparing citizens current tax rates and annual payments to expected payments under any proposed alternative, it is possible to calculate the "Tax Increase in $USD per Household" for each alternative. Finally, using poll results asking whether or not citizens would support a change in tax policy that increased or decreased tax rates for the different income brackets, including their own, it is possible to calculate the "Polling Support in Percent" for each alternative. Table 9 shows the alternatives for this example scored for all fundamental objectives in the value hierarchy.

Table 9: Alternatives by Objective Score-City Tax Example

	Tax Revenue in $USD	Tax Increase in $USD per Household	Polling Support in Percent
Alternative 1	$114,950,000	-$730	51%
Alternative 2	$167,950,000	-$300	45%
Alternative 3	$220,950,000	$120	46%
Alternative 4	$207,875,000	$10	56%
Alternative 5	$260,875,000	$440	46%
Alternative 6	$313,875,000	$860	48%
Alternative 7	$300,800,000	$760	52%
Alternative 8	$353,800,000	$1,180	28%
Alternative 9	$406,800,000	$1,610	46%
Alternative 10	$126,700,000	-$630	55%
Alternative 11	$179,700,000	-$210	64%
Alternative 12	$232,700,000	$220	61%
Alternative 13	$219,625,000	$110	36%
Alternative 14	$272,625,000	$530	21%
Alternative 15	$325,625,000	$960	46%
Alternative 16	$312,550,000	$850	41%
Alternative 17	$365,550,000	$1,280	45%
Alternative 18	$418,550,000	$1,700	57%
Alternative 19	$138,450,000	-$540	27%
Alternative 20	$191,450,000	-$120	31%
Alternative 21	$244,450,000	$310	39%
Alternative 22	$231,375,000	$200	45%
Alternative 23	$284,375,000	$630	55%
Alternative 24	$337,375,000	$1,050	28%
Alternative 25	$324,300,000	$940	23%
Alternative 26	$377,300,000	$1,370	41%
Alternative 27	$430,300,000	$1,790	48%
Status Quo	$231,087,500	$0	43%

3.6 Tradeoff Assessment

In order to get an overall value score for each alternative. The next step is to assess tradeoffs among objectives for DMs. Tradeoffs in the hierarchy convey the comparative prioritization of one objective over another such as economic cost versus social benefit, negative impacts to small groups compared to positive impact to larger groups, or even cost to human life compared to military strategic benefit [7]. There are multiple methods for determining tradeoff information. When converted to a numeric format for the overall value function, tradeoff information is often referred to as the weight given for an objective.

Some weighting methods are more precise than others [101]. For example, rank order weighting methods rely on ordinal information about attribute importance. For example, in the social media problem (see Figure 9) using the rank order weighting method, DMs would have to order 5 attributes in order of most preferred to least preferred. That information would then be converted into the DMs weights for the overall value function. This is a valid weighting method and is often easier than eliciting judgement information specific enough for other weighting methods to be used. But, it is much less precise and less preferred in most circumstances [102].

Compare this to ratio weighting methods, which will be used for the city tax example. Unlike the rank order method, ratio weighting methods preserve DM judgement information beyond just the ordinal properties. This information conveys not just which attribute is preferred, but by how much each attribute is preferred over another [102]. Both the rank order weighting method and ratio weighting method are valid, but they require some form of contact with the DMs in the voting body in order to be legitimate. It is important to note that regardless of the weighting method used for a problem, all weights are, in the end, defined on a ratio scale and sum to 1 for a multi-objective decision analysis problem [102].

3.6.1 <u>Tradeoff Assessment-City Tax Example</u>

One ratio weighting method is called the direct tradeoff method. Direct tradeoffs identify one objective in the value hierarchy and assesses how many units lost in the associated attribute would be equivalent to a unit gained in another objective [102]. Say DM #1, in this example, is presented with a scenario where the solution results in the best possible outcome for the objective “Maximize Tax Revenue” ($430,300,000). That same scenario results in the worst-case results for the objective “Maximize Public Support” (0%). She is then posed with the question, "If 'Tax Revenue in $USD' decreased to $215,150,000 (50% of the maximum possible), how much of an increase in "Public Support in Percent" would need to occur so that you are indifferent between the two options?" She responds by saying that a 50% loss in "Tax Revenue in $USD" is equivalent to a 65% increase in "Public Support in Percent" for the objective "Maximize Public Support." When a similar scenario is presented comparing "Maximize Tax Revenue" to "Minimize Average Tax Increase per Household," she responds by stating that a 50% decrease in "Tax Revenue in $USD" is equivalent to a $1008 decrease (value increase of 40%) in "Tax Increase in $USD per Household" from the max of $1790. Figure 23 shows the tradeoffs for DM #1 with evaluation scales for each attribute.

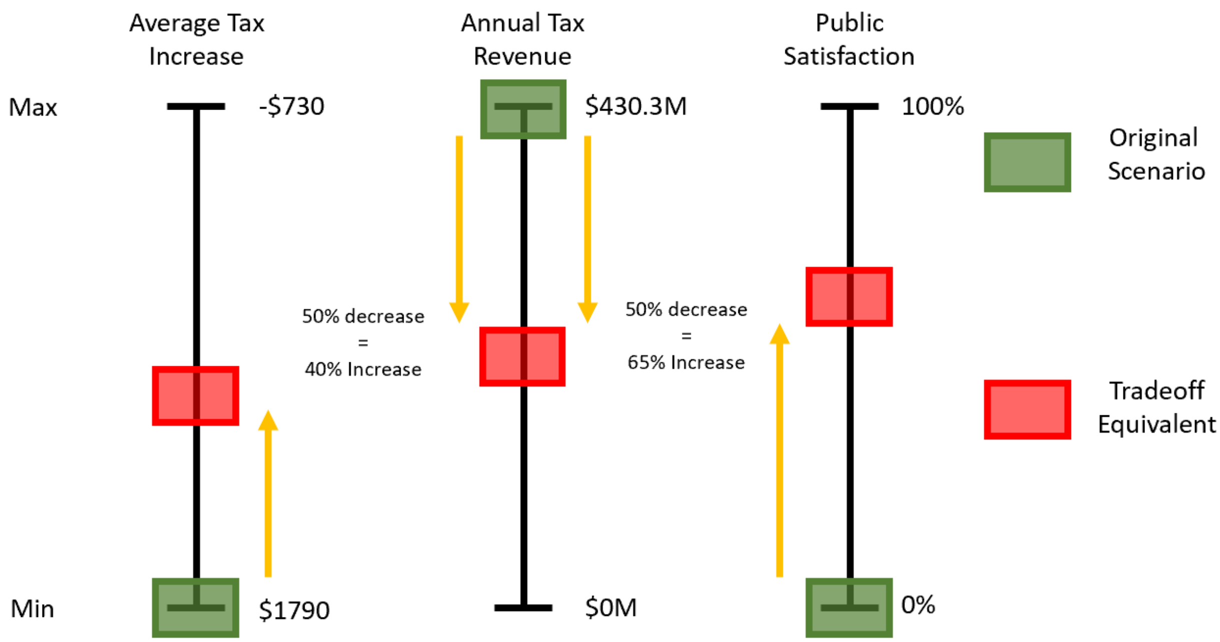


Figure 23: Direct Tradeoff Method for DM #1, City Tax Example

Direct tradeoff values can then be converted to useable weights. First, set the value of the comparison objective (in this example "Maximize Tax Revenue") equal to 1. Next, set the weights for the other two attributes with respect to the comparison attribute (0.77 for "Maximize

Public Support" and 1.2 for "Minimize Average Tax Increase per Household"). Finally, recalculate the weights to sum to 1 by using the equation shown in 5.

$$(5) \qquad w_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

Where w_i is the weight for attribute i and n is the total number of attributes in the value hierarchy. The weights for all 7 DMs in the voting body are given in Table 10.

Table 10: DM Weights, City Tax Example

Weights	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
Annual Tax Revenue	0.34	0.36	0.36	0.38	0.36	0.31	0.29
Average Tax Increase	0.40	0.36	0.32	0.24	0.30	0.35	0.34
Public Satisfaction	0.26	0.28	0.32	0.38	0.34	0.34	0.37

All weights must sum to 1 because the final value function is a weighted average of all the SAVFs in the hierarchy. Once weights are defined, the next step is to determine the aggregation method for the overall value function for the value hierarchy.

3.7 Overall Value Function Aggregation

Once SAVFs and weights have been defined for all attributes, it is possible to assign an overall value score to each alternative. Overall value scores reveal the relative desirability, or preference, of an alternative from the perspective of a given DM. In other words, the aggregated scores capture how a DM views an alternative's performance taking into consideration all objectives in the value hierarchy in a weighted context. The overall value score is what enables further evaluation and analysis of the problem.

An aggregation technique is necessary to generate the overall value score. The two most recognized and widely used aggregation methods are the multiplicative method and the additive method. The multiplicative aggregation method is intended for circumstances where objectives have some sort of interaction amongst themselves. An objective interaction would be where an alternative's poor performance according to one objective guarantees a low value score despite that same alternative performing extremely well for other objectives.

An application of the multiplicative aggregation method is found in a study that sought to identify the best mining method. The multiplicative aggregation made sense in this case because balancing all technological and environmental objectives used for mining method selection made it difficult for DMs to weight the objectives independent of one another. Therefore, the authors of the study elected to use the multiplicative aggregation method to take the interrelations among objectives into consideration [103].

An application of the additive model is found in a study that used MODA to assess employees based on both their competencies and evolution within the company. The study utilized the additive method because their desire was to evaluate employees based on their wholistic performance rather than keying in on any one trait. In this case all of the traits were considered to be independent [70]. The additive method was also used for a MODA study about road designs balancing objectives for longevity, construction price, environmental protection, economic validity, and construction duration [104] and another study to determine the best business strategy for allocating capital and corporate resources [105].

It would be completely acceptable to use the multiplicative aggregation method to calculate overall value scores for each DM for all the alternatives as part of the proposed methodology. However, without obvious presence of interactions between objectives, this methodology will explore the additive aggregation method to calculate overall value scores for the alternatives. The equation used to aggregate SAVF scores derived from the alternatives, accounting for multiple weighted objectives is shown in 6.

$$(6) \quad V_j(x_k) = \sum_{i=1}^{n} w_{ij} v_{ij}(x_k),$$

Where $V_j(x_k)$ is the jth DM's overall value score for alternative k, $i = 1$ to n is the index for the attributes in the value hierarchy, $v_{ij}(x_k)$ is the value score calculated from the SAVF unique to the ith attribute for the jth DM, evaluating alternative k, and w_{ij} is the weight corresponding to the ith attribute considering the jth DM's judgement [64], [68]. In order to demonstrate the additive aggregation method, the city tax problem is continued as an example.

3.7.1 Overall Value Function Aggregation-City Tax Example

With the SAVFs and weights defined for the 3 attributes in the hierarchy for all DMs in the voting body, 7 unique overall value functions can be constructed using the equation shown in 6 to assess alternatives under consideration. The 7 overall value function equations are shown, in order, for DMs 1-7 in 7-13.

$$(7) \quad V_1(x_k) = 0.34v_{1,1}(x_k) + 0.40v_{2,1}(x_k) + 0.26v_{3,1}(x_k)$$

$$(8) \quad V_2(x_k) = 0.36v_{1,2}(x_k) + 0.36v_{2,2}(x_k) + 0.28v_{3,2}(x_k)$$

$$(9) \quad V_3(x_k) = 0.36v_{1,3}(x_k) + 0.32v_{2,3}(x_k) + 0.32v_{3,3}(x_k)$$

$$(10) \quad V_4(x_k) = 0.38v_{1,4}(x_k) + 0.24v_{2,4}(x_k) + 0.38v_{3,4}(x_k)$$

$$(11) \quad V_5(x_k) = 0.36v_{1,5}(x_k) + 0.30v_{2,5}(x_k) + 0.34v_{3,5}(x_k)$$

$$(12) \quad V_6(x_k) = 0.33v_{1,6}(x_k) + 0.34v_{2,6}(x_k) + 0.33v_{3,6}(x_k)$$

$$(13) \quad V_7(x_k) = 0.29v_{1,7}(x_k) + 0.34v_{2,7}(x_k) + 0.36v_{3,7}(x_k)$$

Where $V_j(x_k)$ is the overall value score for the kth alternative according to the jth DM and $v_{i,j}(x_k)$ is the SAVF value score for the ith attribute of kth alternative according to the jth DM. Once the overall value functions for each DM are determined, alternatives can be assessed. The next step of the methodology is testing the model.

3.8 Testing the Model

The value hierarchy is an operational framework once the overall value function is defined. At this point, it is possible to evaluate all alternatives and assign them a value score for each DM in the voting body.

3.8.1 Testing the Model-City Tax Example

Evaluating the 28 alternatives from Table 9 using the equations shown in 7-13 results in 7 rank-ordered list of alternatives. Each list reveals the preference order of all alternatives for each respective DM. Table 11 shows the ranked list for each of the 7 DMs in the voting body.

Table 11: Rank-Ordered List of Alternatives for All DMs-City Tax Example

Rank	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
1	Alt 1	Alt 1	Alt 18	Alt 12	Alt 11	Alt 11	Alt 10
2	Alt 10	Alt 10	Alt 27	Alt 11	Alt 12	Alt 12	Alt 1
3	Alt 11	Alt 11	Alt 10	Alt 4	Alt 4	Alt 10	Alt 11
4	Alt 18	Alt 18	Alt 1	Alt 23	Alt 23	Alt 4	Alt 12
5	Alt 27	Alt 27	Alt 11	Alt 7	Alt 10	Alt 1	Alt 4
6	Alt 2	Alt 2	Alt 9	Status Quo	Alt 7	Status Quo	Alt 2
7	Alt 19	Alt 4	Alt 12	Alt 5	Alt 18	Alt 2	Status Quo
8	Alt 4	Alt 12	Alt 4	Alt 3	Low	Alt 3	Alt 18
9	Alt 12	Alt 9	Alt 2	Alt 6	Status Quo	Alt 23	Alt 23
10	Status Quo	Alt 19	Alt 23	Alt 22	Alt 6	Alt 22	Alt 3
11	Alt 9	Status Quo	Status Quo	Alt 10	Alt 3	Alt 5	Alt 19
12	Alt 3	Alt 23	Alt 17	Alt 15	Alt 5	Alt 7	Alt 7
13	Alt 22	Alt 17	Alt 7	Alt 2	Alt 22	Alt 21	Alt 22
14	Alt 23	Alt 7	Alt 26	Alt 21	Alt 15	Alt 13	Alt 5
15	Alt 20	Alt 3	Alt 3	Alt 16	Alt 2	Alt 6	Alt 27
16	Alt 7	Alt 26	Alt 6	Alt 1	Alt 17	Alt 20	Alt 6
17	Alt 17	Alt 22	Alt 22	Alt 18	Alt 27	Alt 19	Alt 9
18	Alt 26	Alt 6	Alt 15	Alt 13	Alt 9	Alt 15	Alt 20
19	Alt 5	Alt 15	Alt 5	Alt 17	Alt 16	Alt 16	Alt 13
20	Alt 13	Alt 5	Alt 19	Alt 20	Alt 21	Alt 17	Alt 15
21	Alt 6	Alt 20	Alt 16	Alt 26	Alt 26	Alt 14	Alt 21
22	Alt 15	Alt 16	Alt 21	Alt 9	Alt 13	Alt 18	Alt 17
23	Alt 21	Alt 13	Alt 13	Alt 24	Alt 20	Alt 26	Alt 16
24	Alt16	Alt 21	Alt 20	Alt 14	Alt 24	Alt 24	Alt 26
25	Alt 8	Alt 8	Alt 8	Alt 27	Alt 19	Alt 9	Alt 24
26	Alt 24	Alt 24	Alt 24	Alt 8	Alt 8	Alt 25	Alt 8
27	Alt 25	Alt 25	Alt 25	Alt 25	Alt 25	Alt 8	Alt 14
28	Alt 14	Alt 14	Alt 14	Alt 19	Alt 14	Alt 27	Alt 25

The alternatives assessed in a MODA for complex issues can contribute to greater division and unwillingness to compromise among decision makers. When alternatives are selected that only capture vastly different end-states, this may be the case. Whenever a complex issue with multiple competing objectives is being analyzed, it is beneficial to generate multiple alternatives and those alternatives must be related to the values defined by the objectives and fundamental objective specifications in the value hierarchy [101]. This methodology was demonstrated with the city tax example. This step marks the end of alternative assessment. Once alternatives are assessed for all DMs, the next step in the methodology is to forecast votes.

3.9 Forecasting Votes

In order to forecast votes from the DMs, it is necessary to establish an objective threshold between an approving "Yes" vote and a disapproving "No" vote. To do this the methodology will consider what is meant in the political context for a "No" vote. The conclusion drawn was that a "No" vote on any alternative means that the DM prefers the current situation to the proposed alternative. In other words, the DM prefers the status quo. With this in mind, the author conjects that the status quo alternative serves as the benchmark for all DMs in the voting body, separating "Yes" and "No" votes for alternatives. Once DMs' votes are determined, the total number of "Yes" votes received becomes a metric to assess the whether or not an alternative will pass if brought before the voting body.

3.9.1 Forecasting Votes-City Tax Example

This logic was applied to the results of the city tax example. Table 12 is identical to Table 11, except the status quo alternative is highlighted for each DM in the voting body.

Table 12: Rank-Ordered List of Alternatives for All DMs with Identified Thresholds-City Tax Example

Rank	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7
1	Alt 1	Alt 1	Alt 18	Alt 12	Alt 11	Alt 11	Alt 10
2	Alt 10	Alt 10	Alt 27	Alt 11	Alt 12	Alt 12	Alt 1
3	Alt 11	Alt 11	Alt 10	Alt 4	Alt 4	Alt 10	Alt 11
4	Alt 18	Alt 18	Alt 1	Alt 23	Alt 23	Alt 4	Alt 12
5	Alt 27	Alt 27	Alt 11	Alt 7	Alt 10	Alt 1	Alt 4
6	Alt 2	Alt 2	Alt 9	Status Quo	Alt 7	Status Quo	Alt 2
7	Alt 19	Alt 4	Alt 12	Alt 5	Alt 18	Alt 2	Status Quo
8	Alt 4	Alt 12	Alt 4	Alt 3	Low	Alt 3	Alt 18
9	Alt 12	Alt 9	Alt 2	Alt 6	Status Quo	Alt 23	Alt 23
10	Status Quo	Alt 19	Alt 23	Alt 22	Alt 6	Alt 22	Alt 3
11	Alt 9	Status Quo	Status Quo	Alt 10	Alt 3	Alt 5	Alt 19
12	Alt 3	Alt 23	Alt 17	Alt 15	Alt 5	Alt 7	Alt 7
13	Alt 22	Alt 17	Alt 7	Alt 2	Alt 22	Alt 21	Alt 22
14	Alt 23	Alt 7	Alt 26	Alt 21	Alt 15	Alt 13	Alt 5
15	Alt 20	Alt 3	Alt 3	Alt 16	Alt 2	Alt 6	Alt 27
16	Alt 7	Alt 26	Alt 6	Alt 1	Alt 17	Alt 20	Alt 6
17	Alt 17	Alt 22	Alt 22	Alt 18	Alt 27	Alt 19	Alt 9
18	Alt 26	Alt 6	Alt 15	Alt 13	Alt 9	Alt 15	Alt 20
19	Alt 5	Alt 15	Alt 5	Alt 17	Alt 16	Alt 16	Alt 13
20	Alt 13	Alt 5	Alt 19	Alt 20	Alt 21	Alt 17	Alt 15
21	Alt 6	Alt 20	Alt 16	Alt 26	Alt 26	Alt 14	Alt 21
22	Alt 15	Alt 16	Alt 21	Alt 9	Alt 13	Alt 18	Alt 17
23	Alt 21	Alt 13	Alt 13	Alt 24	Alt 20	Alt 26	Alt 16
24	Alt16	Alt 21	Alt 20	Alt 14	Alt 24	Alt 24	Alt 26
25	Alt 8	Alt 8	Alt 8	Alt 27	Alt 19	Alt 9	Alt 24
26	Alt 24	Alt 24	Alt 24	Alt 8	Alt 8	Alt 25	Alt 8
27	Alt 25	Alt 25	Alt 25	Alt 25	Alt 25	Alt 8	Alt 14
28	Alt 14	Alt 14	Alt 14	Alt 19	Alt 14	Alt 27	Alt 25

Alternatives ranking higher than the status quo alternative (those closer to 1), receive a "Yes" vote from that DM. Alternatives ranking lower than the status quo alternative (those closer to 28), receive a "No" vote from that DM. To assess the political viability of the alternatives, the sum of the "Yes" and "No" votes from each DM for each alternative is determined. Table 13 shows the vote totals for the alternatives. The alternatives marked "Low," "Medium," and "High" refer to the base alternatives shown in Table 3.

Table 13: Alternative Vote Totals-City Tax Example

Alternative	"Yes" Votes	"No" Votes
Alternative 1 "Low"	6	1
Alternative 2	4	3
Alternative 3	0	7
Alternative 4	7	0
Alternative 5	0	7
Alternative 6	0	7
Alternative 7	2	5
Alternative 8	0	7
Alternative 9	2	5
Alternative 10	6	1
Alternative 11	7	0
Alternative 12	7	0
Alternative 13	0	7
Alternative 14 "Medium"	0	7
Alternative 15	0	7
Alternative 16	0	7
Alternative 17	0	7
Alternative 18	4	3
Alternative 19	2	5
Alternative 20	0	7
Alternative 21	0	7
Alternative 22	0	7
Alternative 23	3	4
Alternative 24	0	7
Alternative 25	0	7
Alternative 26	0	7
Alternative 27 "High"	3	4
Status Quo Alternative	N/A	N/A

3.10 Analysis

After summing the number of "Yes" and "No" votes each alternative receives, alternatives can be further analyzed, and insights can be provided to the DMs or interested stakeholders.

3.10.1 Analysis-City Tax Example

Table 13 shows the summed votes for each alternative. From these results, we see only 7 of the 27 proposed alternatives received a majority of 4 or more "Yes" votes from the council.

Based on these findings, the analyst could submit a final product to whomever requested the study. The final product could be a list of the 7 passing alternatives with their performance in each attribute, including votes received. Table 14 shows what a final product summary for the city tax example could look like.

Table 14: Final Product Summary-City Tax Example

	Tax Rates by Income Bracket						
Alternative	**<$100,000 per year**	**$100,000-$500,000 per year**	**>$500,000 per year**	**Tax Revenue in $USD**		**Constituent Satisfaction**	**Expected "Yes" Votes**
Alternative 1	0%	0.5%	1%	$114,950,000	-$730	51%	6
Alternative 2	0%	0.5%	2%	$167,950,000	-$300	45%	4
Alternative 4	0%	1.25%	1%	$207,875,000	$10	56%	7
Alternative 10	0.5%	0.5%	1%	$126,700,000	-$630	55%	6
Alternative 11	0.5%	0.5%	2%	$179,700,000	-$210	64%	7
Alternative 12	0.5%	0.5%	3%	$232,700,000	$220	61%	7
Alternative 18	0.5%	2.0%	3%	$418,550,000	$1,700	57%	4

The information contained in the final product summary is intended to provide additional points of reference to assist decision makers by narrowing the solution space to more productive areas. As this methodology is intended to be utilized for decision aid rather than decision making [62], narrowing down to a single alternative is ultimately left up to the decision maker(s).

3.11 Conclusion

In this chapter, the methodology for developing an effective multi-objective decision analysis (MODA) to assess competing objectives for multiple decision makers was laid out. An explanation was provided for how to both construct and gather the information for a valid value hierarchy - the elements of which include the overall fundamental objective, fundamental objectives, and fundamental objective specifications. Two examples of value hierarchies were given for a corporate executive board and an appointed military voting commission. In order to make the value hierarchy an operational framework, this chapter explained techniques for selecting and defining attributes, developing SAVFs, assessing tradeoffs, and aggregating scores to produce an overall value score for multiple alternatives. Finally, this chapter detailed a novel methodology to forecast votes by assessing alternatives using the overall value functions. An example of a local city tax policy is applied to demonstrate operationalizing a value hierarchy and forecasting votes for a city council consisting of 7 members. This methodology is applied in chapter 4 to evaluate the issue of United States-Mexico border security that led to a 35-day partial government shutdown in December 2018 [28], [33], [106].

Chapter 4: Experiment

4.1 Experiment Introduction

In order to show the potential of the proposed methodology, this chapter evaluates the case of United States border security. This case was selected for evaluation due to the currency of the issue in addition to the decision characteristics of the problem. In December 2018, a dispute over border security funding led to a 35-day partial government shutdown that directly affected thousands of people's lives and held the attention of the worldwide media [32], [107], [108]. As discussed in Chapter 2, the United States Border Patrol (USBP), under direction of Customs and Border Protection (CBP), is primarily responsible for traffic enforcement on the United States-Mexico border [42]. As is the case with any government department or agency, however, USBP is not the decision maker (DM) determining their annual budget, nor are they the DM to determine the allocation of funds within that budget [4]. However, they still act as a major stakeholder with an input [3], [12]. The budget for border security is decided by the United States Congress as part of the national budget for each fiscal year [5]. With an understanding of this background, this chapter sets forth a border security scenario as an experiment to test the vote forecasting methodology described in Chapter 3.

4.1.1 Experiment Scenario

The scenario for this experiment is a simplified version of events towards the end of the 35-day government shutdown. CBP is faced with the task of submitting a border security proposal to the voting body regarding the 1150 unfenced miles of the U.S. Southwest border (SWB). The voting body consists of 20 DMs, with 10 belonging to the Gold party and 10 belonging to the Silver Party. CBP has its own objectives, which may or may not align with the objectives of any of the DMs in the voting body, but their primary goal is to submit a proposal that is both beneficial to the agency and also politically viable. CBP defines politically viable as having a moderate likelihood of receiving a majority of "Yes" votes (11 or more) from the voting body. The proposal submitted by CBP contains a request for funding of 3 separate border security technologies: a physical barrier or “wall,” aerial surveillance, and ground-based surveillance. These technology areas were identified by CBP due to their current use in other areas along the SWB [3], [109], [110], as well as their support from DMs in past border security proposals [33], [56], [86]. These 3 technologies are further defined, for this scenario, as a steel slated fence (Figure 24) for the wall [111], [112], the MQ-9 Predator B drone (Figure 25) for aerial surveillance [3], [113], and the integrated-fixed tower system, or IFT (Figure 26), for ground-based surveillance [110], [114].

Figure 24: Section of Bollard Barrier Steel Slated Fence currently in use along the United States Southwest Border [111]

Figure 25: Fleet of 3 MQ-9 Predator B UAS operated by CBP [113]

Figure 26: Constructed Tower and Sensors for the Integrated Fixed Towers (IFT) System [114]

For this scenario, the funding for these 3 technologies is independent of and in addition to the standard operations and maintenance costs incurred by CBP. In other words, CBP will receive funding to continue uninterrupted operations regardless of additional funds for technologies requested in the proposal. In this scenario, 20 alternatives are assessed. Each alternative is comprised of different funding allotments for each of the 3 technologies. Because of this, alternatives for this scenario are hereafter referred to as portfolio alternatives (PAs). Table 15 shows the 20 PAs defined according to the funding allotment in billions $USD. Table 16 shows the same 20 PAs defined by the miles of coverage provided by each technology based on the funding allotments. For information on how miles of coverage were calculated for each technology, see Appendix 1. Funding allotments for all PAs were derived from actual proposals or bills brought before the public or Congress around the time of the 35-day shutdown [4], [9], [13], [115].

Table 15: Portfolio Alternatives by Funding Allotments [4], [9], [13], [115]

Dollars Allotted ($B)	Wall	Aerial Surveillance	Ground-Based Surveillance
Portfolio Alternative 1	$0.000	$0.000	$0.000
Portfolio Alternative 2	$1.600	$0.000	$0.000
Portfolio Alternative 3	$5.700	$0.000	$0.000
Portfolio Alternative 4	$23.000	$0.000	$0.000
Portfolio Alternative 5	$25.000	$0.000	$0.000
Portfolio Alternative 6	$0.000	$0.000	$0.182
Portfolio Alternative 7	$1.600	$0.000	$0.182
Portfolio Alternative 8	$5.700	$0.000	$0.182
Portfolio Alternative 9	$23.000	$0.000	$0.182
Portfolio Alternative 10	$25.000	$0.000	$0.182
Portfolio Alternative 11	$0.000	$0.183	$0.182
Portfolio Alternative 12	$1.600	$0.183	$0.182
Portfolio Alternative 13	$5.700	$0.183	$0.182
Portfolio Alternative 14	$23.000	$0.183	$0.182
Portfolio Alternative 15	$25.000	$0.183	$0.182
Portfolio Alternative 16	$0.000	$0.183	$0.000
Portfolio Alternative 17	$1.600	$0.183	$0.000
Portfolio Alternative 18	$5.700	$0.183	$0.000
Portfolio Alternative 19	$23.000	$0.183	$0.000
Portfolio Alternative 20	$25.000	$0.183	$0.000

Table 16: Portfolio Alternatives by Miles of Coverage

Miles of Coverage	Wall	Aerial Surveillance	Ground-Based Surveillance	No Barrier
Portfolio Alternative 1	0	0	0	1150
Portfolio Alternative 2	73.6	0	0	1076.4
Portfolio Alternative 3	262.2	0	0	887.8
Portfolio Alternative 4	1058	0	0	92
Portfolio Alternative 5	1150	0	0	0
Portfolio Alternative 6	0	0	78.442	1071.558
Portfolio Alternative 7	73.6	0	78.442	997.958
Portfolio Alternative 8	262.2	0	78.442	809.358
Portfolio Alternative 9	1058	0	78.442	13.558
Portfolio Alternative 10	1150	0	78.442	0
Portfolio Alternative 11	0	438.468	78.442	633.09
Portfolio Alternative 12	73.6	438.468	78.442	559.49
Portfolio Alternative 13	262.2	438.468	78.442	370.89
Portfolio Alternative 14	1058	438.468	78.442	0
Portfolio Alternative 15	1150	438.468	78.442	0
Portfolio Alternative 16	0	438.468	0	711.532
Portfolio Alternative 17	73.6	438.468	0	637.932
Portfolio Alternative 18	262.2	438.468	0	449.332
Portfolio Alternative 19	1058	438.468	0	0
Portfolio Alternative 20	1150	438.468	0	0

Presented with this scenario, the proposed methodology is used to assess the PAs and forecast votes for the different DMs in the voting body. The experiment begins by structuring the problem and constructing a value hierarchy.

4.2 The Value Hierarchy-Border Security

In order to establish the value hierarchy, 2 different diagrams were used to structure the problem and provide further insight. The first is an interrelationship diagram (Figure 27) to better understand cause-and-effect relationships for the border security problem. The diagram begins with the node in the top-left corner “SWB is vulnerable to illegal trafficking of persons and illicit substances.” The diagram finishes at any of the 4 nodes on the right-hand side. These nodes constitute potential desired outcomes, or objectives, that are considered by the DMs in the voting body. Information from a combination of Gold and Silver Standard documents was used to construct each of the two diagrams and the eventual value hierarchy [40], [54], [55].

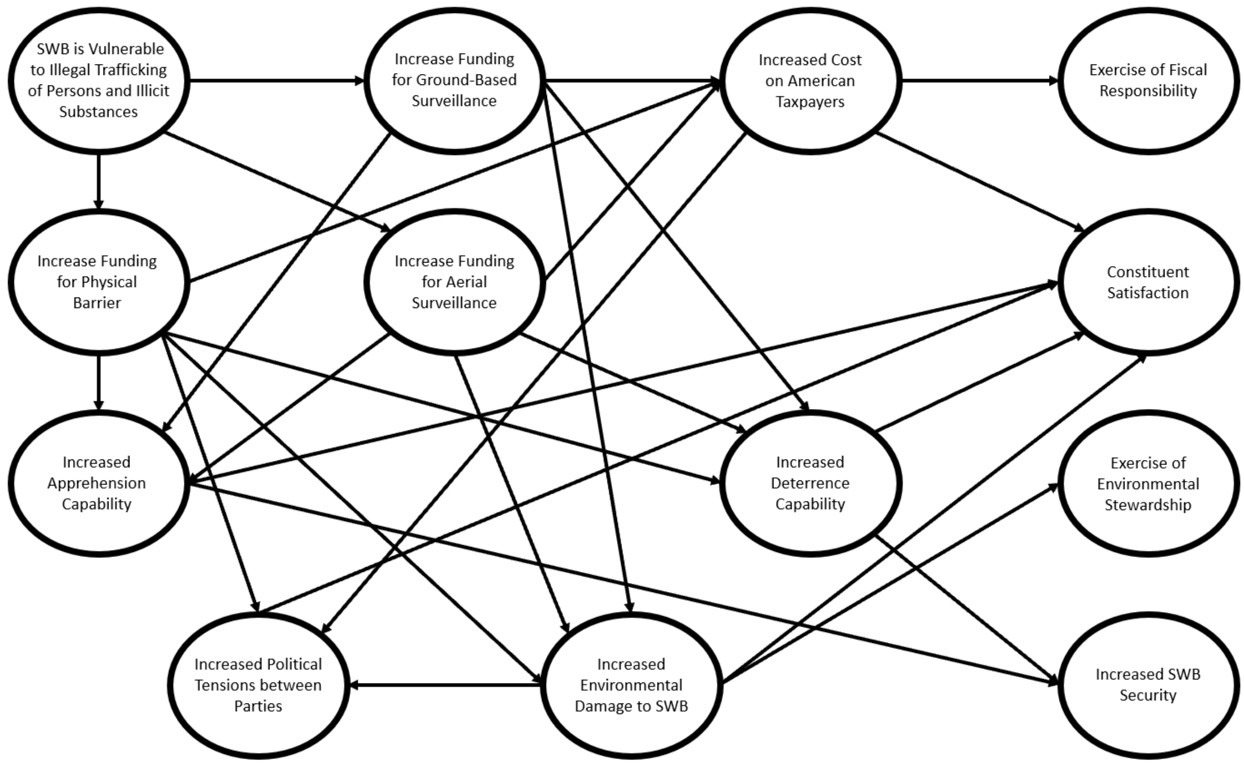


Figure 27: Interrelationship Diagram-Border Security

The interrelationship diagram begins with the situation of the vulnerable SWB. This situation, in turn, causes the need for a decision to increase funding allotments for the physical barrier, aerial surveillance, and/or ground-based surveillance. The decision made for each of these technologies is expected to result in increased apprehension [16] and deterrence capabilities [46]. These abilities tie to the desired outcome, or objective, of increased border security. Another expected effect of increasing funding for any of the technologies is increased cost to for American taxpayers [14], [110], [116]. Increased taxpayer costs directly affect the objective to exercise fiscal responsibility. Increased funding for a physical barrier is also expected to increase tensions between political parties [24], [117]. Increased funding for any of the technologies is expected to have a negative environmental impact [112]. This directly ties to the objective to exercise environmental stewardship. Increased apprehension and deterrence capability, increased political tensions, increased taxpayer cost, and increased environmental impact all affect the desired objective of constituent satisfaction [23].

The information from the interrelationship diagram was translated into an affinity diagram for better organization (Figure 28) [64]. To capture true DM objectives, a top layer of objectives was included to reflect elected officials' priorities when making policy decisions. These additional objectives are, establish the best funding strategy for constituents, establish the best funding strategy for personal ideology, and establish the best funding strategy for the political party of which the DM is a member [58]. In addition to the top-level objectives, objectives for increased border security, fiscal responsibility, and environmental stewardship were further defined.

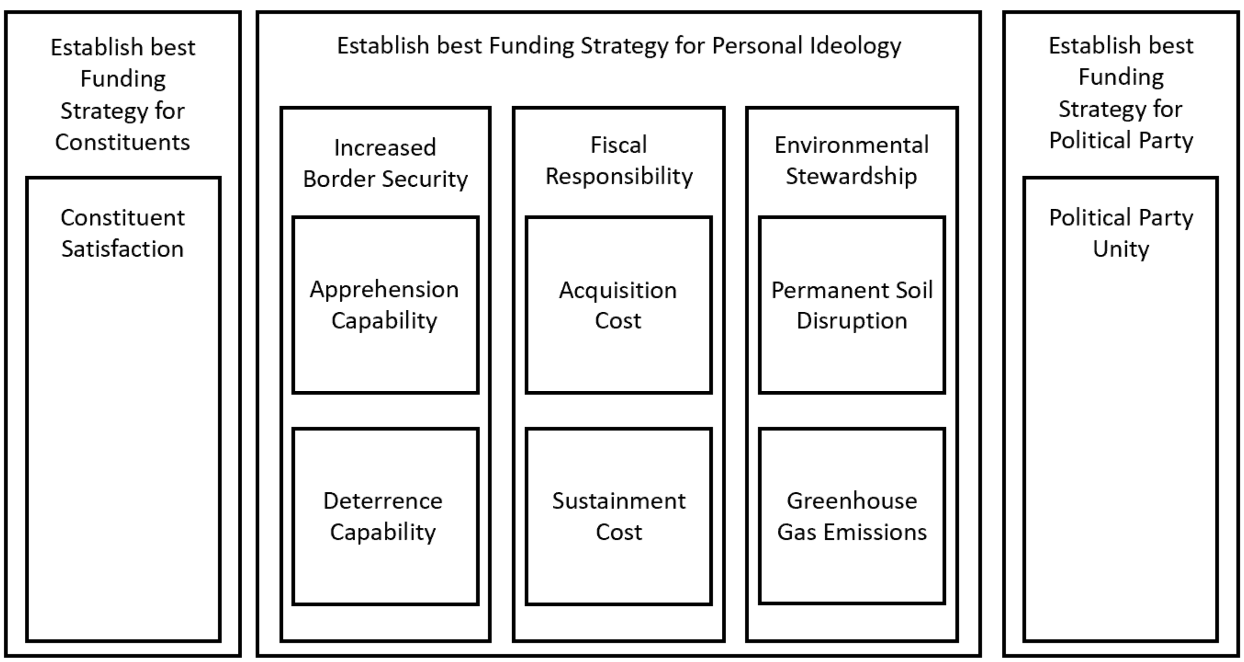


Figure 28: Affinity Diagram-Border Security

Using the basic organization provided by the affinity diagram, the value hierarchy for border security was constructed according to the proposed methodology (Figure 29). The overall fundamental objective for the hierarchy is “Establish the Best Funding Strategy for the 1150 miles of Unfenced Border between the U.S. and Mexico.” The three fundamental objectives are “Maximize Constituent Satisfaction” [54], [55], “Maximize Adherence to Personal Ideology” [58], and “Maximize Party Unity” [118], The fundamental objectives “Maximize Constituent Satisfaction” and “Maximize Party Unity” were determined to not require any fundamental objective specifications. However, the fundamental objective “Maximize Adherence to Personal Ideology” is further defined with 6 fundamental objective specifications. Those fundamental objective specifications are “Maximize Apprehension Capability,” “Maximize Deterrence Capability,” “Minimize Acquisition Cost,” “Minimize Sustainment Cost,” “Minimize Permanent Soil Disruption,” and “Minimize Greenhouse Gas Emissions” [54], [55], [119]–[121].

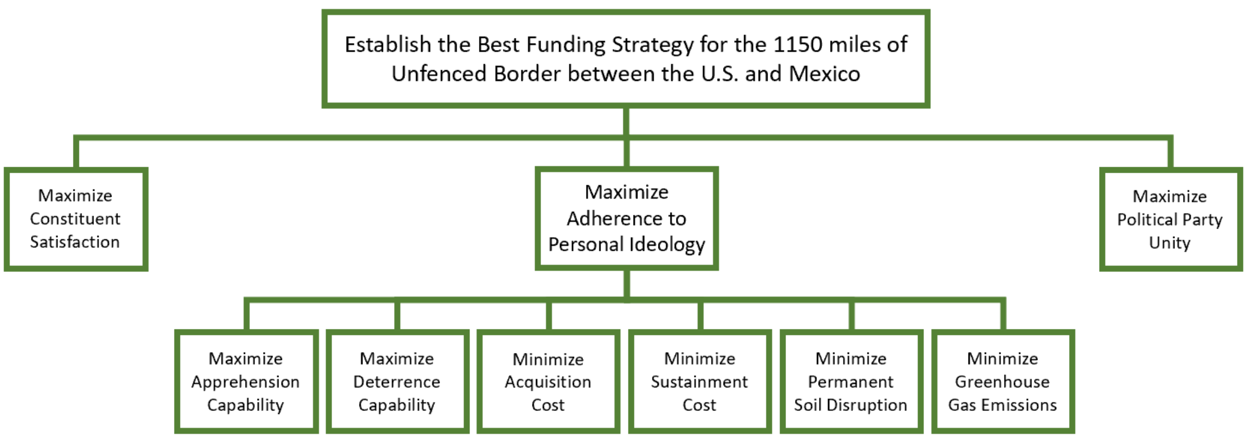


Figure 29: Value Hierarchy-Border Security

In order to assess the PAs, the value hierarchy will be made into an operational framework in accordance with the methodology.

4.3 <u>Attribute Definition-Border Security</u>

The first step to make the value hierarchy an operational framework is to associate each objective with an attribute and define it.

4.3.1 Attribute for Constituent Satisfaction

There is no direct measure for constituent satisfaction. Typically, satisfaction information is gathered in the form of opinion polls. Multiple polls exist capturing constituents' opinions about SWB border security [24], [25], [119]. Based on these polls, a proxy attribute is proposed for this objective [20]. The proposed attribute quantifies the degree to which alternatives increase or decrease constituent satisfaction. This attribute ranges from 0% as the lowest, or worst, impact level to 100% as the highest, or best, impact level.

4.3.2 Attribute for Apprehension Capability

Apprehension capability is not a directly measurable attribute. To measure apprehension capability, this experiment uses the proxy attribute average expected apprehension rate over the 1150 miles of the SWB under consideration. Apprehension rates are common metrics used by CBP. These rates are also averaged over distances, such as sectors [16]. Therefore, based on the criteria, this is considered a natural attribute [64], [91]. Like constituent satisfaction, this attribute ranges from 0% as the lowest impact level to 100% as the highest impact level.

4.3.3 Attribute for Deterrence Capability

Apprehension and deterrence are two sides of the border enforcement coin. Apprehension deals with would-be illegal crossers, preventing them from entering the country at the border. Deterrence, on the other hand, discourages would-be illegal crossers from ever beginning the journey. While these two attributes share a common purpose, literature shows them to be largely independent of one another [46]. CBP has no established metric for tracking deterrence, as it is difficult to count people that never turn up to be counted. Thus, for this objective, the attribute is a direct, constructed measure generated by the author [64], [91].

For this experiment, deterrence is measured on a mile-by-mile basis, for the 1150 miles under consideration, with a score ranging from 0 and 5. The score for the mile of deployed technology corresponds to the values in Table 17.

Table 17: SWB Deterrence Score Evaluation Table

Deterrence Score	Description of Deterrence Level
0	Provides no opposition to illegal border crossings
1	Presents no physical opposition but could reasonably result in some psychological concern
2	Presents visual evidence to dissuade crossing (knowledge you are being tracked)
3	Presents physical obstacle making travel difficult but not impossible for any individual
4	Presents significant physical obstacle making travel difficult or impossible without additional equipment
5	Presents physical obstacle making travel impossible for any individual with or without additional equipment

Each PA's mile-by-mile deterrence scores are summed to equal the final deterrence value for the alternative. This attribute ranges in value from 0 as the lowest impact level to 5750 as the highest impact level. In truth, the highest possible number for this attribute is 8,050, based on the PAs. However, because no PAs in the experiment perform close to this high, the upper limit was set to 5,750. This number is equivalent to a 5-rated deterrence technology deployed along the entire 1150 miles of the SWB considered in the scenario.

4.3.4 Attribute for Acquisition Cost

The cost of a PA can be accounted for using two methods, either by evaluating acquisition cost and sustainment cost independently, or evaluating the lifecycle cost as a single attribute. A lifecycle cost implies a system with a known end of life [122]. Government systems are frequently utilized well beyond their intended lifecycle, such as the C-5 Galaxy transport aircraft [17] and the Hubble Space Telescope [19]. This being the reality, for this experiment, the author elected to evaluate acquisition and sustainment cost as independent attributes. Acquisition cost is measured in billions $USD. It is a direct-natural attribute, commonly used and wholly encompassing the objective [64], [91]. This attribute ranges from $30 billion as the lowest impact level to $0 as the highest impact level.

4.3.5 Attribute for Annual Sustainment Cost

Sustainment cost is a direct and natural attribute, commonly used and wholly encompassing the objective [64], [91]. It is measured in millions $USD per year. This attribute ranges from $350M per year as the lowest impact level, to $0 per year as the highest impact level. In truth, the highest number possible for annual sustainment cost, were all 3 technologies deployed over the 1150 miles, is over $1.65 billion per year. As no PAs evaluated in this experiment amount to a sustainment cost near that cost, the upper limit for sustainment cost was set at $350M per year.

4.3.6 Attribute for Permanent Soil Disruption

Environmental stewardship was broken down into two objectives, minimize permanent soil disruption and minimize greenhouse gas emissions. CBP analyzes technologies according to both criteria when conducting environmental assessments [11]. Permanent soil disruption is measured in acres, which makes it a natural attribute. It also directly assesses the objective to minimize permanent soil disruption [64], [91]. This attribute ranges from 3500 acres as the lowest impact level to 0 acres as the highest impact level. The highest possible number for this attribute, if all 3 technologies were funded across all 1150 miles, would be 7,475 acres of permanent soil disruption. As no PAs in this experiment equate to near that many acres, the upper limit for sustainment cost was set at 3500 acres.

4.3.7 Attribute for Greenhouse Gas Emissions

Greenhouse gas emissions are frequently measured in terms of CO2 equivalents. CO2 equivalents equate the effects of all greenhouse gases produced from a technology and defines the output as if all emissions were CO2 [123]. Though it was originally a constructed measure, the commonality of CO2 equivalents as a metric qualify this as a natural attribute [91]. It also directly measures the objective for minimizing greenhouse gas emissions [64], [91]. For this experiment, CO2 equivalent emissions are measured over the life of the technology in million metric tons (Mmt). This attribute ranges from 90 Mmt as the lowest impact level to 0 Mmt as the highest impact level.

4.3.8 Attribute for Political Party Unity

The final attribute is based on the objective to maximize party unity. There is no way to measure party unity until after the vote is cast. However, voting body structures provide ways to assess party unity via a proxy attribute, party leader support. In the United States House of Representatives and the Senate, there are elected officials known as the majority and minority leaders. These party leaders are elected by the other members in their chamber because of their perceived influence and ability to unite other party members [124]. In the scenario for this experiment, the Gold Party and Silver Party similarly have their respective party leaders. Based on this voting body structure, the attribute for maximizing party unity is a natural-proxy measure where each alternative is assessed to determine whether it receives support from either the Gold Party or Silver Party leader. This attribute has a binary value of 0 and 1, where 0 is the lowest impact level and 1 is the highest impact level.

4.3.9 Summary of Border Security Attributes

With all attributes now defined, Figure 30 shows the value hierarchy with each objective further defined by the associated attribute.

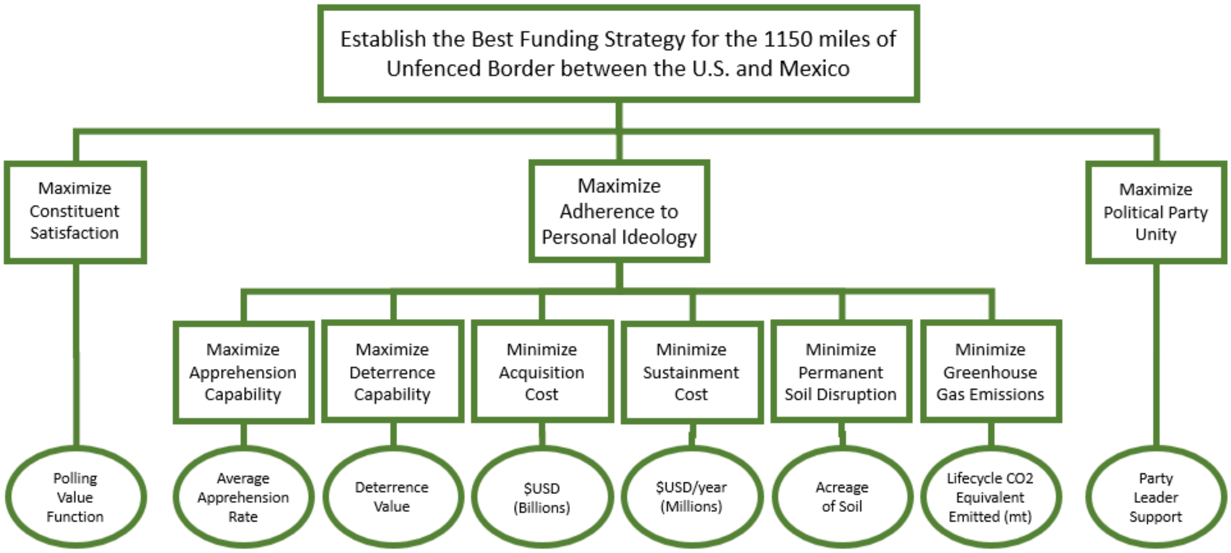


Figure 30: Value Hierarchy with Attributes-Border Security

4.4 Single Attribute Value Functions-Border Security

Once all fundamental objectives and fundamental objective specifications are assigned attributes, a single attribute value function (SAVF) is associated with each attribute for each DM in the voting body. This requires identifying mid-values for each attribute for each DM. For further details for how the simulated voting body was generated to produce necessary mid-values for the SAVFs, see Appendix II. The equation that gives a value score for attributes defined with the exponential function is show in 14 for increasing SAVFs and 15 for decreasing SAVFs [68].

$$(14) \qquad v_{ijk}(x_{ij}, \rho_{ik}) = \begin{cases} \dfrac{1 - e^{[-(x_{ij} - x_{Low})/\rho_{ik}]}}{1 - e^{[-(x_{High} - x_{Low})/\rho_{ik}]}}, & when\ \rho_{ik} \neq Infinity \\ \dfrac{x_{ij} - x_{Low}}{x_{High} - x_{Low}}, & otherwise \end{cases}$$

$$(15) \qquad v_{ijk}(x_{ij}, \rho_{ik}) = \begin{cases} \dfrac{1 - e^{[-(x_{High} - x_{ij})/\rho_{ik}]}}{1 - e^{[-(x_{High} - x_{Low})/\rho_{ik}]}}, & when\ \rho_{ik} \neq Infinity \\ \dfrac{x_{ij} - x_{Low}}{x_{High} - x_{Low}}, & otherwise \end{cases}$$

Where $v_{ijk}(x_{ij}, \rho_{ik})$ is the single attribute value score of the ith attribute for the jth PA according to the preferences of the kth DM in the voting body, x_{ij} is the attribute score of the

ith attribute for the jth PA, x_{High} is the upper limit for the attribute, x_{Low} is the lower limit for the attribute, and ρ_{ik} is the exponential constant for the ith attribute defined by the mid-value given by the kth DM in the voting body.

4.4.1 SAVF for Constituent Satisfaction

As mentioned in section 4.3, limits for constituent satisfaction were set at 0% for the lowest impact level and 100% for the highest impact level. Figure 31 and Figure 32 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively. Arrows in the figure indicate the direction of increasing value for the DM.

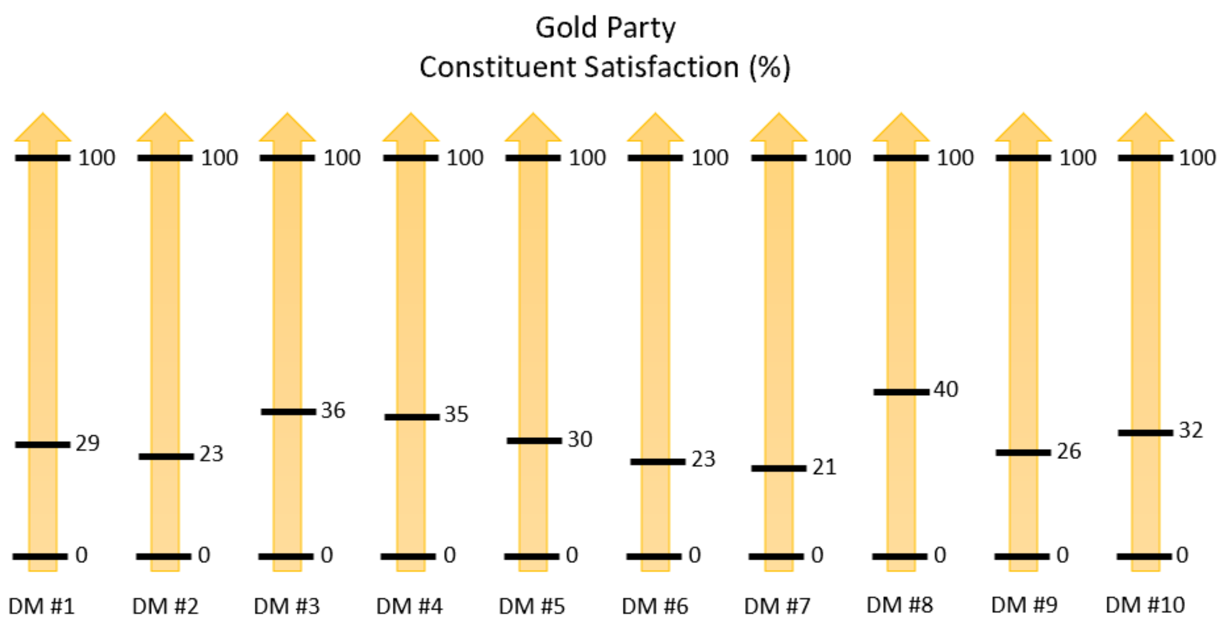


Figure 31: Evaluation Scales-Gold Party Constituent Satisfaction

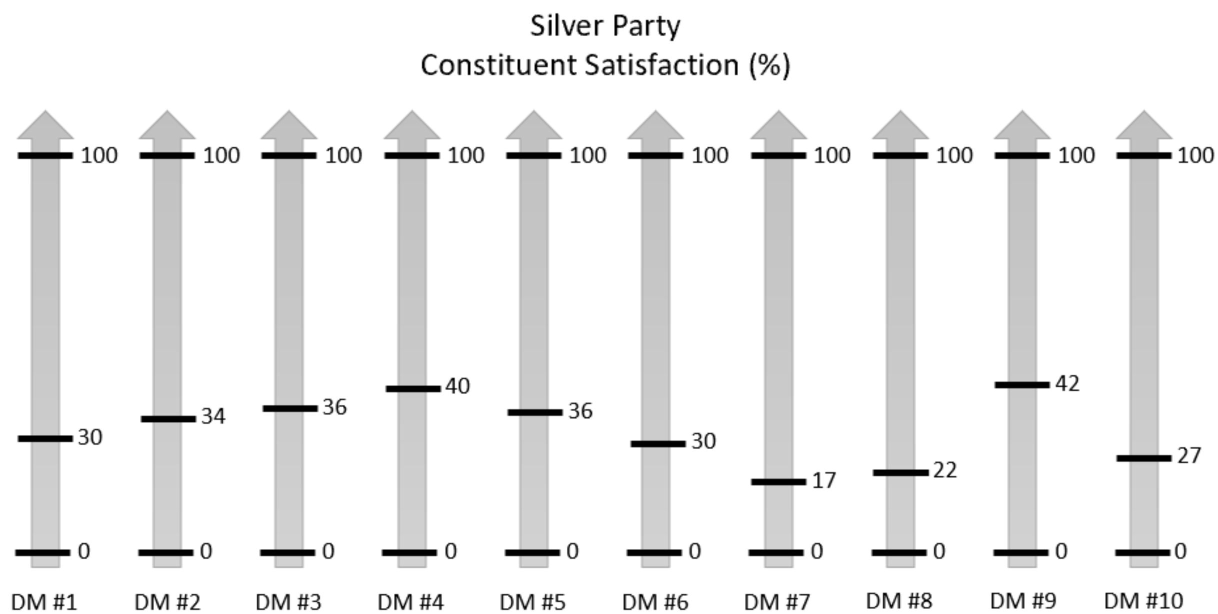


Figure 32: Evaluation Scales-Silver Party Constituent Satisfaction

Table 18 and Table 19 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the constituent satisfaction SAVF for each DM in the Gold Party and Silver Party respectively.

Table 18: Mid-Value and Exponential Constants-Gold Party Constituent Satisfaction, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	29	23	36	35	30	23	21	40	26	32
$z_{0.5}$	0.71	0.77	0.64	0.65	0.7	0.77	0.79	0.6	0.74	0.68
R	-0.522	-0.365	-0.845	-0.782	-0.555	-0.365	-0.324	-1.216	-0.435	-0.638
$\rho_{1,k}$	-52.2	-36.5	-84.5	-78.2	-55.5	-36.5	-32.4	-121.6	-43.5	-63.8

Table 19: Mid-Value and Exponential Constants-Silver Party Constituent Satisfaction, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	30	34	36	40	36	30	17	22	42	27
$z_{0.5}$	0.70	0.66	0.64	0.60	0.64	0.70	0.83	0.78	0.58	0.73
R	-0.555	-0.726	-0.845	-1.216	-0.845	-0.555	-0.252	-0.344	-1.536	-0.462
$\rho_{1,k}$	-55.5	-72.6	-84.5	-121.6	-84.5	-55.5	-25.2	-34.4	-153.6	-46.2

With the limits and respective mid-values, the SAVF for constituent satisfaction can be derived for each DM in the voting body. Constituent satisfaction is an increasing function. The equation that gives the constituent satisfaction value score for each PA is shown in 16.

$$v_{1,j,k}(x_{1,j}, \rho_{1,k}) = \begin{cases} \dfrac{1 - e^{[(-x_{1,j} - 0)/\rho_{1,k}]}}{1 - e^{[-(100-0)/\rho_{1,k}]}}, & when\ \rho_{1,k} \neq Infinity \\ \dfrac{x_{1,j} - 0}{100 - 0}, & otherwise \end{cases} \quad (16)$$

Where $v_{1,j,k}(x_{1,j}, \rho_{1,k})$ is the constituent satisfaction single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{1,j}$ is the variable objective score from the PA, and $\rho_{1,k}$ is the constituent satisfaction exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the constituent satisfaction SAVF defined, the next attribute in the value hierarchy is apprehension capability.

4.4.2 SAVF for Apprehension Capability

The limits for this attribute were set as 0% for the lowest impact level and 100% for the highest impact level. Figure 33 and Figure 34 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

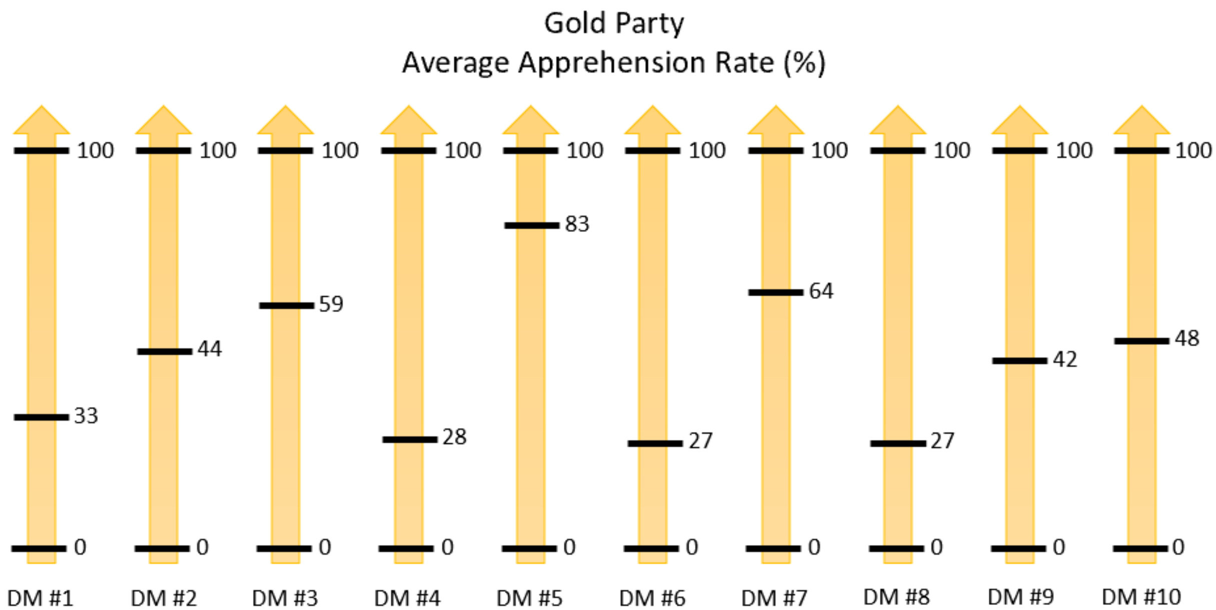


Figure 33: Evaluation Scales-Gold Party Average Apprehension Rate

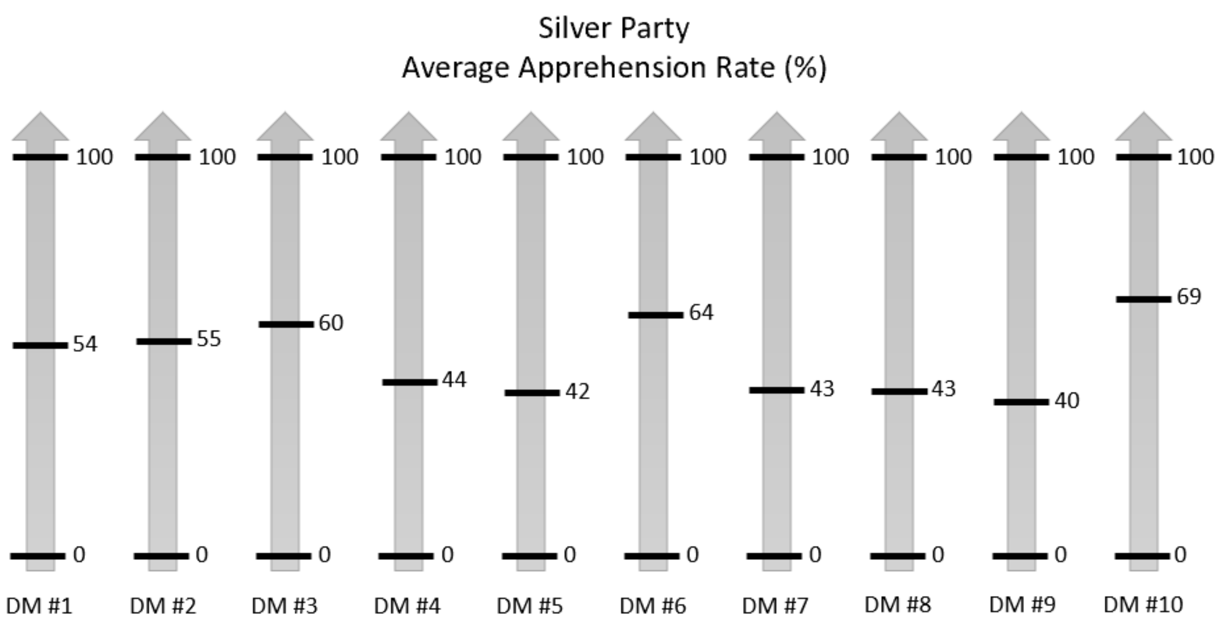


Figure 34: Evaluation Scales-Gold Party Average Apprehension Rate

Table 20 and Table 21 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the apprehension capability SAVF for each DM in the Gold Party and Silver Party respectively.

Table 20: Mid-Value and Exponential Constants-Gold Party Average Apprehension Rate, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	33	44	59	28	83	27	64	27	42	48
$z_{0.5}$	0.67	0.56	0.41	0.72	0.17	0.73	0.36	0.73	0.58	0.52
R	-0.677	-2.063	1.359	-0.491	0.252	-0.462	0.845	-0.462	-1.536	-6.243
$\rho_{2,k}$	-67.7	-206.3	135.9	-49.1	25.2	-46.2	84.5	-46.2	-153.6	-624.3

Table 21: Mid-Value and Exponential Constants-Silver Party Average Apprehension Rate, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	54	55	60	44	42	64	43	43	40	69
$z_{0.5}$	0.46	0.45	0.40	0.56	0.58	0.36	0.57	0.57	0.60	0.31
R	3.112	2.483	1.216	-2.063	-1.536	0.845	-1.762	-1.762	-1.216	0.592
$\rho_{2,k}$	311.2	248.3	121.6	-206.3	-153.6	84.5	-176.2	-176.2	-121.6	59.2

With the limits and respective mid-values, the SAVF for average apprehension rate can be derived for each DM in the voting body. Average apprehension rate is an increasing function. The equation that gives the average apprehension rate value score for each PA is shown in 17.

$$(17) \qquad v_{2,j,k}\left(x_{2,j}, \rho_{2,k}\right) = \begin{cases} \dfrac{1 - e^{[(-x_{2,j}-0)/\rho_{2,k}]}}{1 - e^{[-(100-0)/\rho_{2,k}]}}, & when\ \rho_{2,k} \neq Infinity \\ \dfrac{x_{2,j} - 0}{100 - 0}, & otherwise \end{cases}$$

Where $v_{2,j,k}\left(x_{2,j}, \rho_{2,k}\right)$ is the average apprehension rate single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{2,j}$ is the variable objective score for the PA, and $\rho_{2,k}$ is the average apprehension rate exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the average apprehension rate SAVF defined, the next attribute in the value hierarchy is deterrence capability.

4.4.3 SAVF for Deterrence Capability

The limits for the deterrence capability attribute were set as 0 for the lowest impact level and 5,750 for the highest impact level. Figure 35 and Figure 36 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

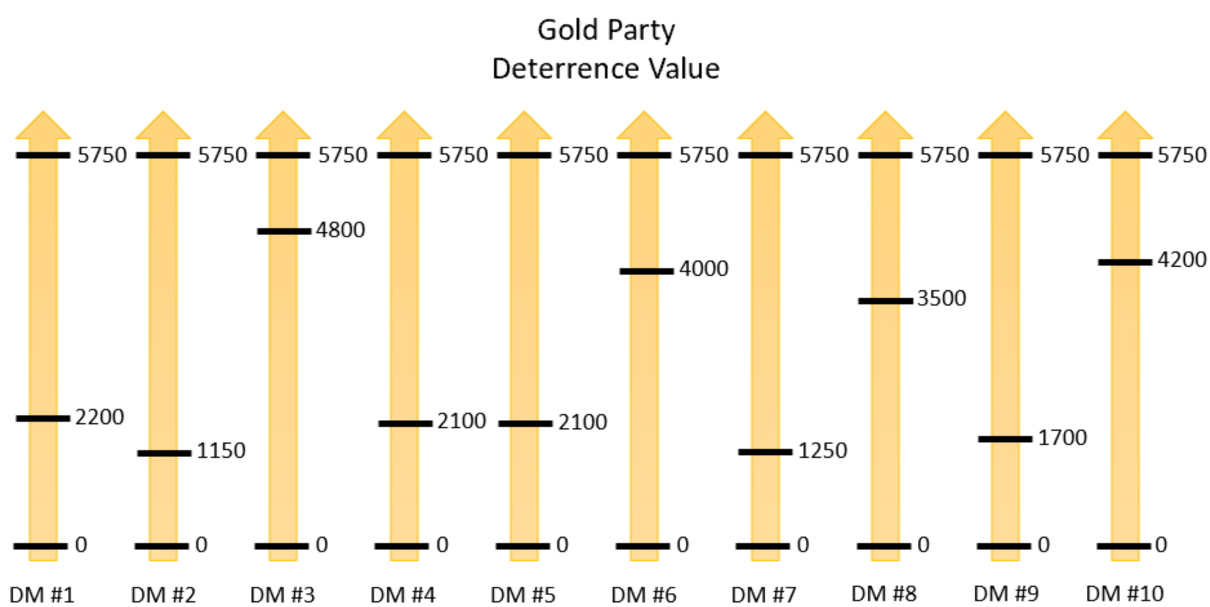


Figure 35: Evaluation Scales-Gold Party Deterrence Value

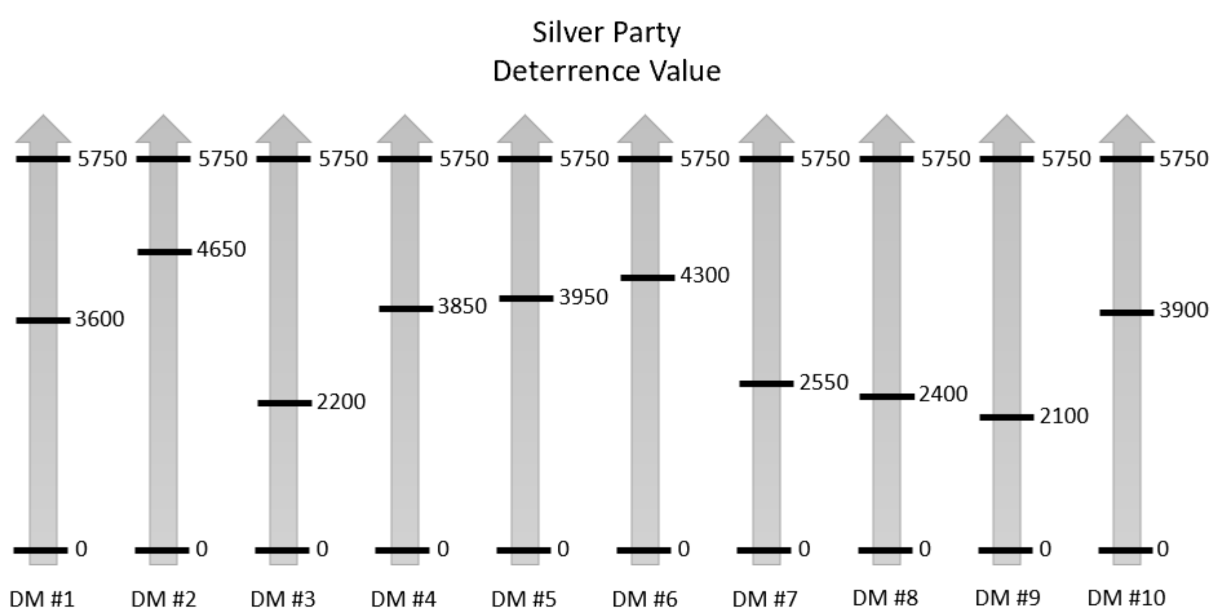


Figure 36: Evaluatin Scales-Silver Party Deterrence Value

Table 22 and Table 23 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the SAVF for each DM in the Gold Party and Silver Party respectively.

Table 22: Mid-Value and Exponential Constants-Gold Party Deterrence Value, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	2200	1150	4800	2100	2100	4000	1250	3500	1700	4200
$z_{0.5}$	0.62	0.8	0.17	0.63	0.63	0.30	0.78	0.39	0.70	0.27
R	-1.001	-0.305	0.252	-0.917	-0.917	0.555	-0.344	1.099	-0.555	0.462
ρ	-5756	-1754	1449	-5273	-5273	3191	-1978	6319	-3191	2657

Table 23: Mid-Value and Exponential Constants-Silver Party Deterrence Value, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	3600	4650	2200	3850	3950	4300	2550	2400	2100	3900
$z_{0.5}$	0.37	0.19	0.62	0.33	0.31	0.25	0.56	0.58	0.63	0.32
R	0.917	0.287	-1.001	0.677	0.592	0.410	-2.063	-1.536	-0.917	0.632
ρ	5273	1650	-5756	3893	3404	2358	-11862	-8832	5273	3634

With the limits and respective mid-values, the SAVF for deterrence can be derived for each DM in the voting body. Deterrence is an increasing function. The equation that gives the deterrence value score for each PA is shown in 18.

$$v_{3,j,k}(x_{3,j}, \rho_{3,k}) = \begin{cases} \dfrac{1 - e^{[(-x_{3,j} - 0)/\rho_{3,k}]}}{1 - e^{[-(5750-0)/\rho_{3,k}]}}, & when\ \rho_{3,k} \neq Infinity \\ \dfrac{x_{3,j} - 0}{5750 - 0}, & otherwise \end{cases} \tag{18}$$

Where $v_{3,j,k}(x_{3,j}, \rho_{3,k})$ is the deterrence single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{3,j}$ is the variable objective score for the PA, and $\rho_{3,k}$ is the deterrence exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the deterrence SAVF defined, the next attribute in the value hierarchy is acquisition cost.

4.4.4 SAVF for Acquisition Cost

The limits for acquisition cost were set at $30 billion for the lowest impact level and $0 for the highest impact level. Figure 37 and Figure 38 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

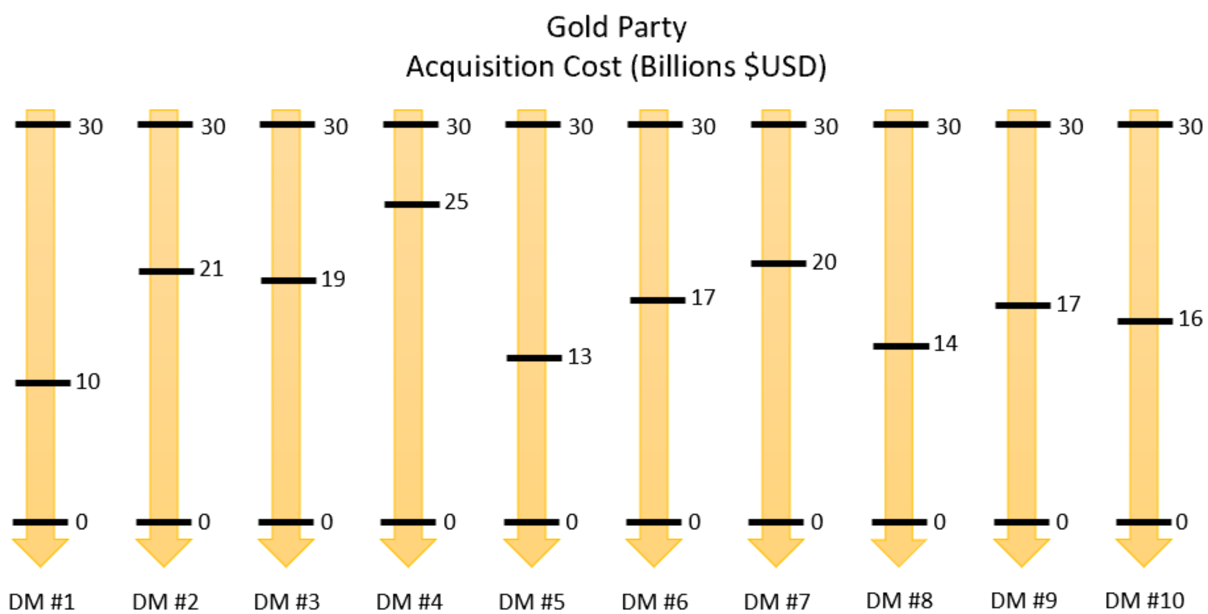


Figure 37: Evaluation Scales-Gold Party Acquisition Cost

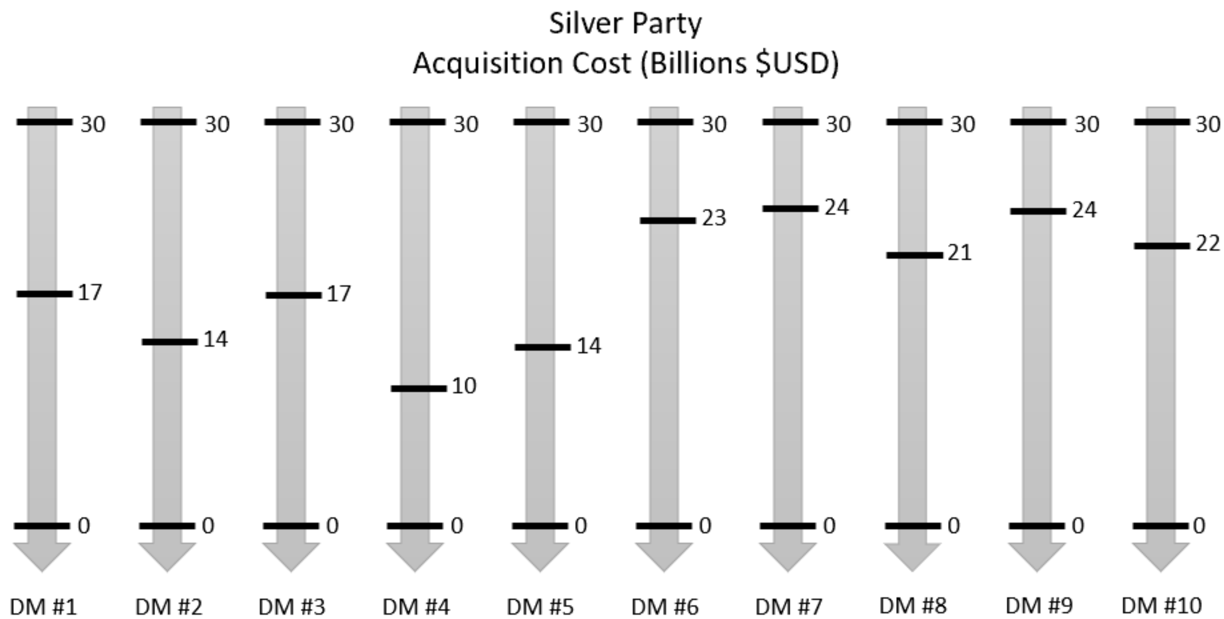


Figure 38: Evaluation Scales-Silver Party Acquisition Cost

Table 24 and Table 25 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the SAVF for each DM in the Gold Party and Silver Party respectively.

Table 24: Mid-Value and Exponential Constants-Gold Party Acquisition Cost, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	10	21	19	25	13	17	20	14	17	16
$z_{0.5}$	0.33	0.70	0.63	0.83	0.43	0.57	0.67	0.47	0.57	0.53
R	0.667	-0.555	-0.917	-0.252	1.762	-1.762	-0.677	4.157	-1.762	-4.157
ρ	20.31	-16.65	-27.51	-7.56	52.86	-52.86	-20.31	124.7	-52.86	-124.7

Table 25: Mid-Value and Exponential Constants-Silver Party Acquisition Cost, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	17	14	17	10	14	23	24	21	24	22
$z_{0.5}$	0.57	0.47	0.57	0.33	0.47	0.77	0.80	0.70	0.80	0.73
R	-1.762	4.157	-1.762	0.677	4.157	-0.365	-0.305	-0.555	-0.305	-0.462
ρ	-52.86	124.7	-52.86	20.31	124.7	-10.95	-9.15	-16.65	-9.15	-13.86

With the limits and respective mid-values, the SAVF for acquisition cost can be derived for each DM in the voting body. Acquisition cost is a decreasing function. The equation that gives the acquisition cost value score for each PA is shown in 19.

$$(19) \qquad v_{4,j,k}(x_{4,j}, \rho_{4,k}) = \begin{cases} \dfrac{1 - e^{[-(30-x_{4,j})/\rho_{4,k}]}}{1 - e^{[-(30-0)/\rho_{4,k}]}}, & when\ \rho_{4,k} \neq Infinity \\ \dfrac{30 - x_{4,j}}{30 - 0}, & otherwise \end{cases}$$

Where $v_{4,j,k}(x_{4,j}, \rho_{4,k})$ is the acquisition cost single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{4,j}$ is the variable objective score for the PA, and $\rho_{4,k}$ is the acquisition cost exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the acquisition cost SAVF defined, the next attribute in the value hierarchy is sustainment cost.

4.4.5 <u>SAVF for Sustainment Cost</u>

The limits for the sustainment cost attribute were set as \$350 million per year for the lowest impact level and \$0 per year for the highest impact level. Figure 39 and Figure 40 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

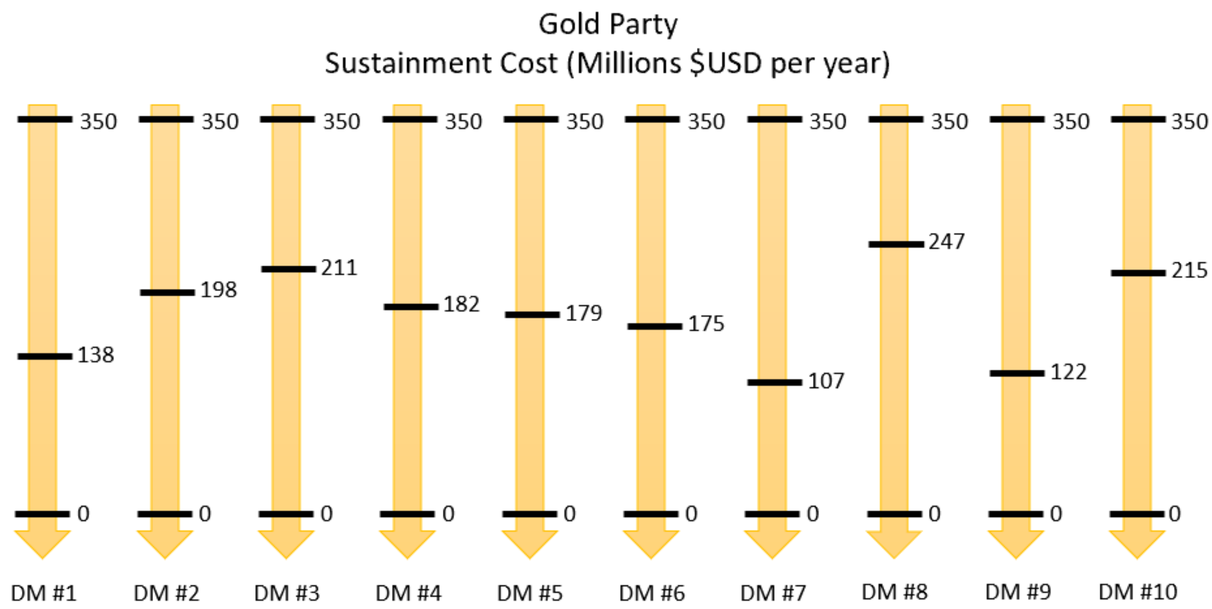


Figure 39: Evaluation Scales-Gold Party Sustainment Cost

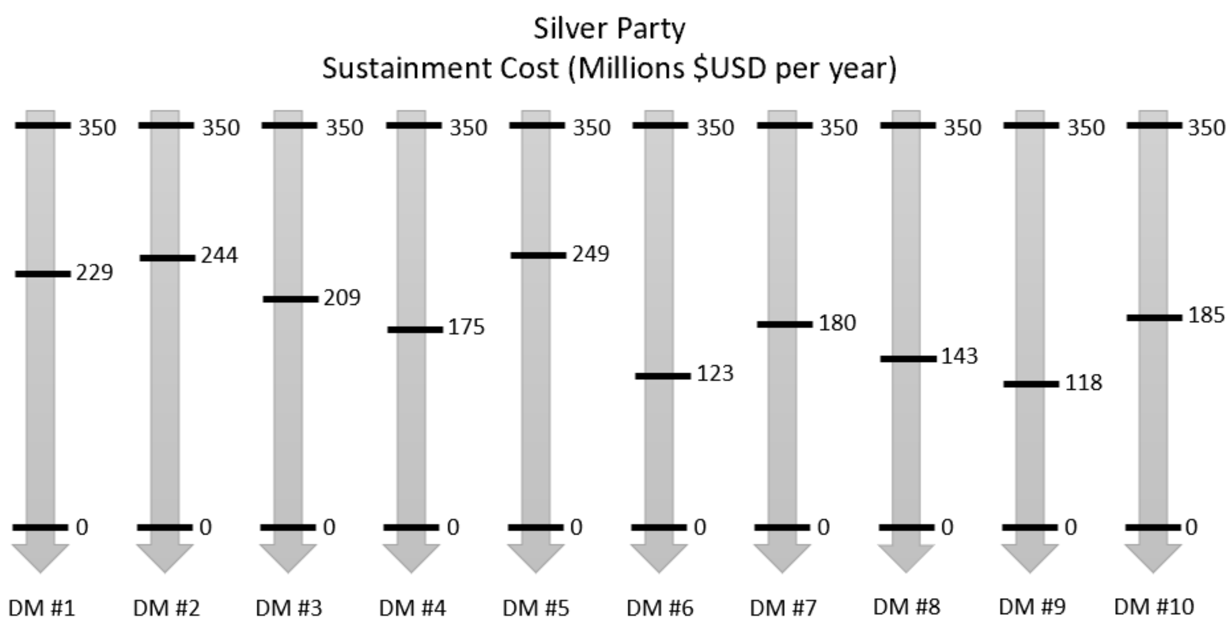


Figure 40: Evaluation Scales-Silver Party Sustainment Cost

Table 26 and Table 27 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the SAVF for each DM in the Gold Party and Silver Party respectively.

Table 26: Mid-Value and Exponential Constants-Gold Party Sustainment Cost, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	138	198	211	182	179	175	107	247	122	215
$z_{0.5}$	0.39	0.57	0.60	0.52	0.51	0.50	0.31	0.71	0.35	0.61
R	1.099	-1.762	-1.216	-6.243	-12.50	Infinity	0.592	-0.522	0.782	-1.099
ρ	384.7	-616.7	-425.6	-2815	-4374	Infinity	207.2	-182.7	273.7	-384.7

Table 27: Mid-Value and Exponential Constants-Silver Party Sustainment Cost, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	229	244	209	175	249	123	180	143	118	185
$z_{0.5}$	0.65	0.70	0.60	0.50	0.71	0.35	0.51	0.41	0.34	0.53
R	-0.782	-0.555	-1.216	Infinity	-0.522	0.782	-12.50	1.359	0.726	-4.157
ρ	-273.7	-194.3	-425.6	Infinity	-182.7	273.7	-4374	475.7	254.1	-1455

With the limits and respective mid-values, the SAVF for sustainment cost can be derived for each DM in the voting body. Sustainment cost is a decreasing function. The equation that gives the sustainment cost value score for each PA is shown in 20.

$$(20) \qquad v_{5,j,k}(x_{5,j}, \rho_{5,k}) = \begin{cases} \dfrac{1 - e^{[-(350 - x_{5,j})/\rho_{5,k}]}}{1 - e^{[-(350-0)/\rho_{5,k}]}}, & when\ \rho_{5,k} \neq Infinity \\ \dfrac{350 - x_{5,j}}{350 - 0}, & otherwise \end{cases}$$

Where $v_{5,j,k}(x_{5,j}, \rho_{5,k})$ is the sustainment cost single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{5,j}$ is the variable objective score for the PA, and $\rho_{5,k}$ is the sustainment cost exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the sustainment cost SAVF defined, the next attribute in the value hierarchy is permanent soil disruption.

4.4.6 SAVF for Permanent Soil Disruption

The limits for the permanent soil disruption attribute were set as 3500 acres for the lowest impact level and 0 acres for the highest impact level. Figure 41 and Figure 42 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

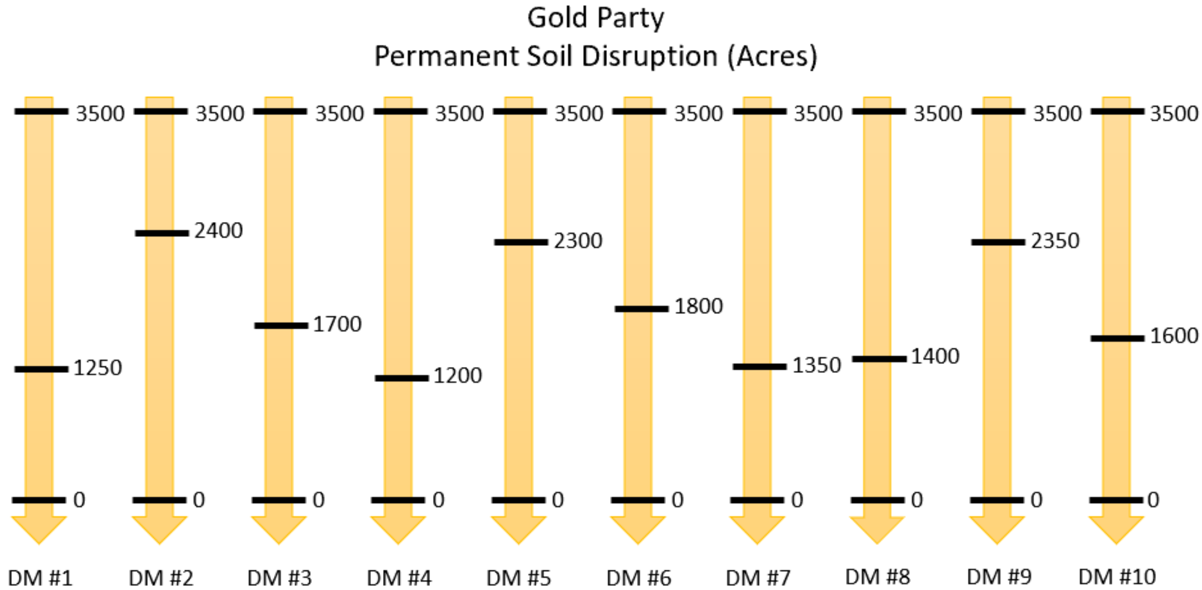


Figure 41: Evaluation Scales-Gold Party Permanent Soil Disruption

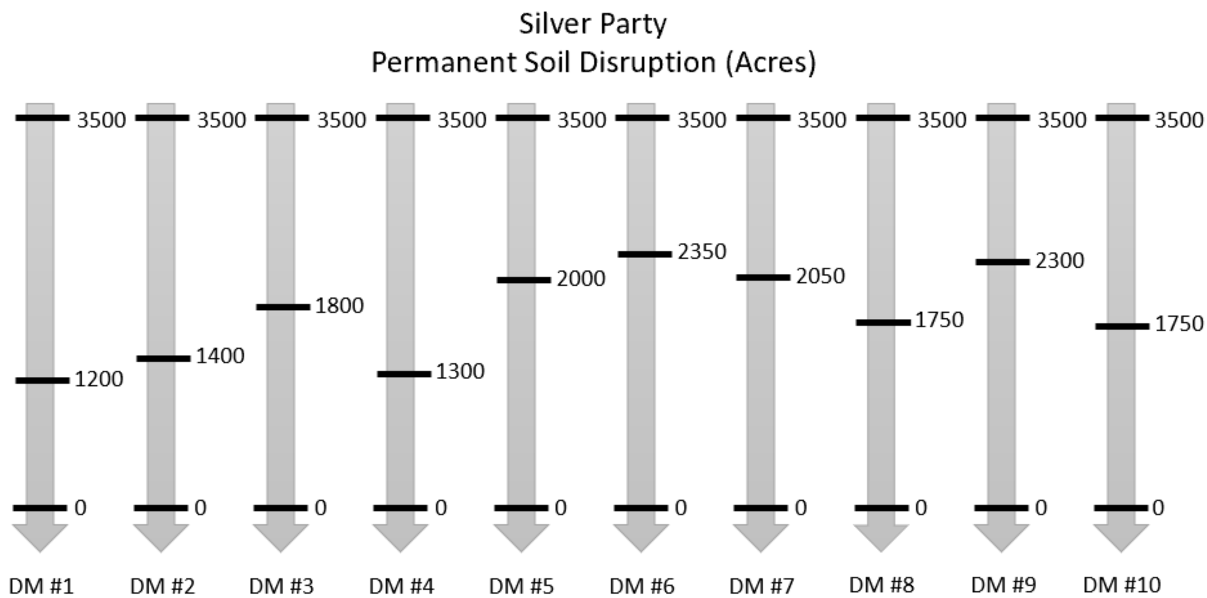


Figure 42: Evaluation Scales-Silver Party Permanent Soil Disruption

Table 28 and Table 29 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the SAVF for each DM in the Gold Party and Silver Party respectively.

Table 28: Mid-Value and Exponential Constants-Gold Party Permanent Soil Disruption, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	1250	2400	1700	1200	2300	1800	1350	1400	2350	1600
$z_{0.5}$	0.36	0.69	0.49	0.34	0.66	0.51	0.39	0.40	0.67	0.46
R	0.845	-0.592	12.50	0.726	-0.726	-12.50	1.099	1.216	-0.677	3.112
ρ	-273.7	-194.3	-425.6	Infinity	-182.7	273.7	-4374	475.7	254.1	-1455

Table 29: Mid-Value and Exponential Constants-Silver Party Permanent Soil Disruption, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	1200	1400	1800	1300	2000	2350	2050	1750	2300	1750
$z_{0.5}$	0.34	0.40	0.51	0.37	0.57	0.67	0.59	0.50	0.66	0.50
R	0.726	1.216	-12.50	0.917	-1.762	-0.677	-1.359	Infinity	-0.726	Infinity
ρ	2958	-2072	43740	2541	-2541	-43740	3847	4256	-2370	10890

With the limits and respective mid-values, the SAVF for permanent soil disruption can be derived for each DM in the voting body. Permanent soil disruption is a decreasing function. The equation that gives the permanent soil disruption value score for each PA is shown in 21.

$$v_{6,j,k}(x_{6,j}, \rho_{6,k}) = \begin{cases} \dfrac{1 - e^{[-(3500 - x_{6,j})/\rho_{6,k}]}}{1 - e^{[-(3500-0)/\rho_{6,k}]}}, & when\ \rho_{6,k} \neq Infinity \\ \dfrac{3500 - x_{6,j}}{3500 - 0}, & otherwise \end{cases} \tag{21}$$

Where $v_{6,j,k}(x_{6,j}, \rho_{6,k})$ is the permanent soil disruption single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{6,j}$ is the variable objective score for the PA, and $\rho_{6,k}$ is the permanent soil disruption exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the permanent soil disruption SAVF defined, the next attribute in the value hierarchy is greenhouse gas emissions.

4.4.7 SAVF for Greenhouse Gas Emissions

The final metric for greenhouse gas emissions is given in terms of million metric tons (Mmt) of CO2 equivalent lifecycle emissions. The limits for greenhouse gas emissions were set as 90 Mmt of CO2 equivalent lifecycle emissions for the lowest impact level and 0 Mmt for the highest impact level. Figure 43 and Figure 44 show the evaluation scales with the limits and mid-value for each DM in the Gold Party and Silver Party respectively.

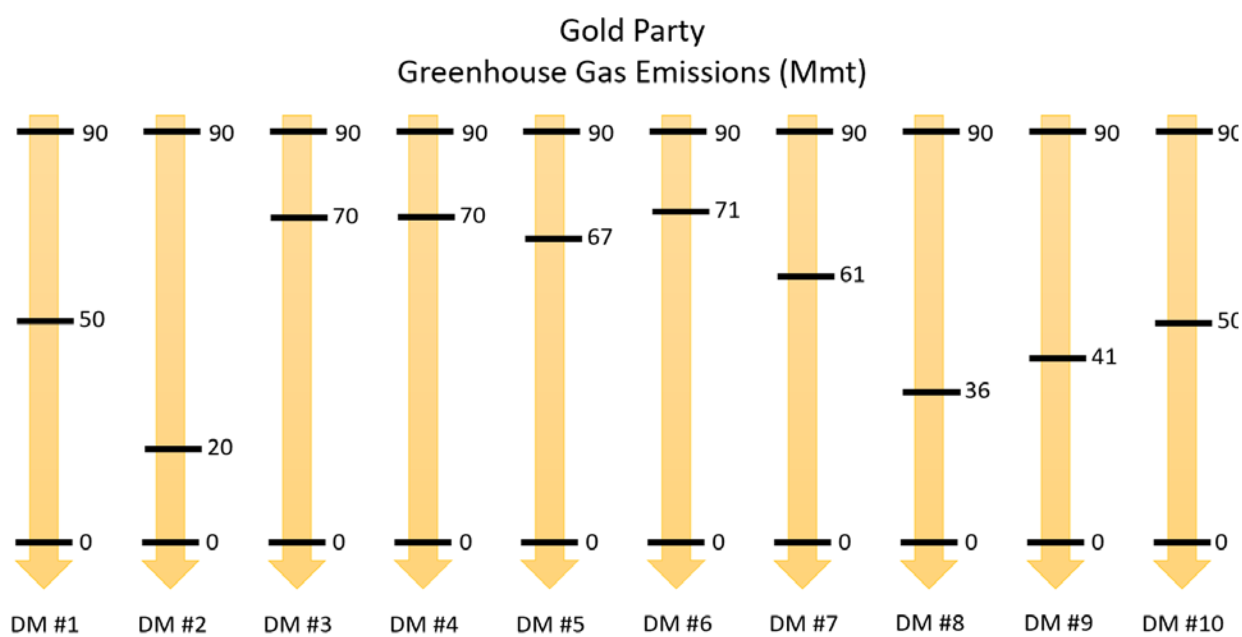


Figure 43: Evaluation Scales-Gold Party Greenhouse Gas Emissions

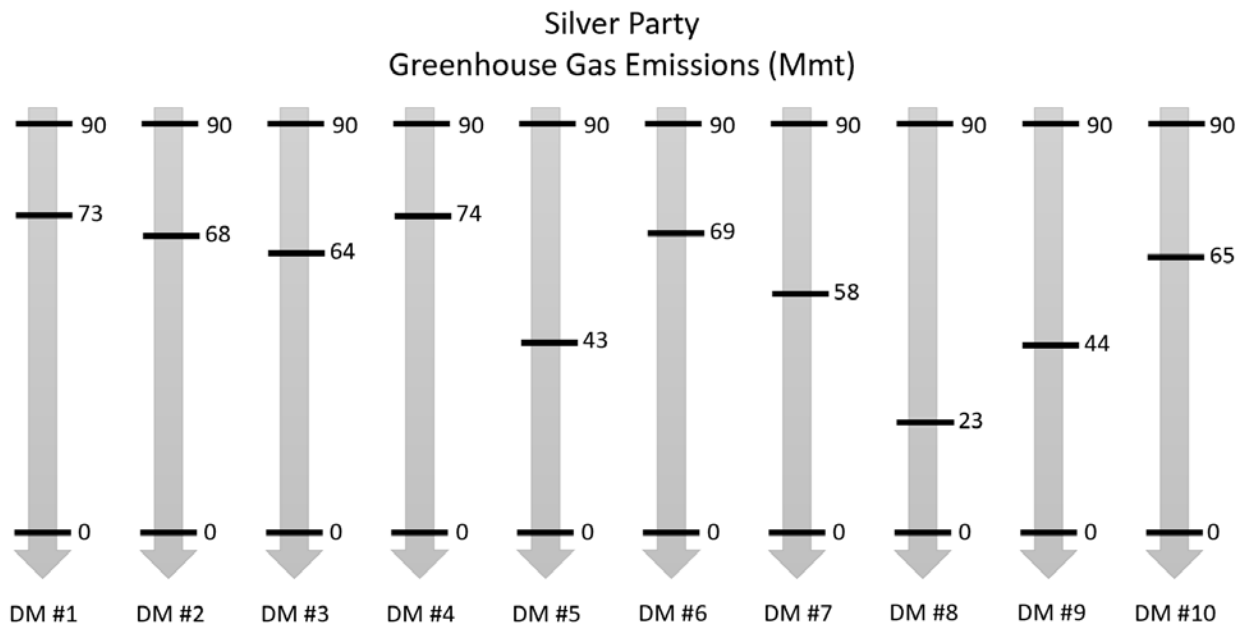


Figure 44: Evaluation Scales-Silver Party Greenhouse Gas Emissions

Table 30 and Table 31 show the mid-values, normalized mid-values, normalized exponential constants, and exponential constants to define the SAVF for each DM in the Gold Party and Silver Party respectively.

Table 30: Mid-Value and Exponential Constants-Gold Party Greenhouse Gas Emissions, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	50	20	70	70	67	71	61	36	41	50
$z_{0.5}$	0.56	0.22	0.78	0.78	0.74	0.79	0.68	0.40	0.46	0.56
R	-2.063	0.344	-0.344	-0.344	-0.435	-0.324	-0.632	1.216	3.112	-2.063
ρ	-185.7	30.96	-30.96	-30.96	-39.15	-29.15	-56.88	109.44	280.1	-185.7

Table 31: Mid-Value and Exponential Constants-Silver Party Greenhouse Gas Emissions, Border Security

	DM #1	DM #2	DM #3	DM #4	DM #5	DM #6	DM #7	DM #8	DM #9	DM #10
Mid-Value	73	68	64	74	43	69	58	23	44	65
$z_{0.5}$	0.81	0.76	0.71	0.82	0.48	0.77	0.64	0.26	0.49	0.72
R	-0.287	-0.387	-0.522	-0.269	6.243	-0.365	-0.845	0.435	12.50	-0.491
ρ	-25.83	-34.83	-46.98	-24.21	561.9	-32.9	-76.05	39.15	1125	-44.19

With the limits and respective mid-values, the SAVF for greenhouse gas emissions can be derived for each DM in the voting body. Greenhouse gas emissions is a decreasing function. The equation that gives the greenhouse gas emissions value score for each PA is shown in 22.

$$(22) \qquad v_{7,j,k}(x_{7,j}, \rho_{7,k}) = \begin{cases} \dfrac{1 - e^{[-(90-x_{7,j})/\rho_{7,k}]}}{1 - e^{[-(90-0)/\rho_{7,k}]}}, & when\ \rho_{7,k} \neq Infinity \\ \dfrac{90 - x_{7,j}}{90 - 0}, & otherwise \end{cases}$$

Where $v_{7,j,k}(x_{7,j}, \rho_{7,k})$ is the greenhouse gas emissions single attribute value score for the jth PA according to the preferences of the kth DM in the voting body, $x_{7,j}$ is the variable objective score for the PA, and $\rho_{6,k}$ is the greenhouse exponential constant defined by the mid-value given by the kth DM in the voting body. Now, with the greenhouse gas emissions SAVF defined, the final attribute in the value hierarchy is to measure political party unity.

4.4.8 SAVF for Party Unity

Because the attribute for party unity is a binary function, the SAVF is equivalent to the variable objective score for the PA. The equation that gives the party unity value score for each PA is shown in 23.

$$(23) \qquad v_{8,j}(x_{8,j}) = x_{8,j}$$

Where $v_{8,j}(x_{8,j})$ is the single attribute value score for the PA and $x_{8,j}$ is the variable objective score for the PA.

4.5 Scoring PAs for Single Objectives

Once the SAVF for each attribute for each DM in the voting body is defined, the next step is to determine the equations to score a PA for each objective. Because alternatives are portfolios of different technologies, it is necessary to define much of the scoring first by technology, then by the PA as a whole.

4.5.1 Scoring PAs for Constituent Satisfaction

The equation to score constituent satisfaction is broken down by technology and by political party. It is assumed that satisfaction for any individual technology is independent of satisfaction for another technology. Thus, each constituent's satisfaction with a PA is an average of that constituent's satisfaction with each individual technology.

Technology 1: The Wall

To begin, constituents from the respective political parties have significantly different opinions on the wall. According to research center data, 82% of Gold Party constituents favor substantially expanding the wall along the U.S. border with Mexico. Only 6% of Silver Party constituents favor the same. The same poll indicates that 84% of Silver Party constituents would not have been willing to reopen the government during the shutdown if it required funding the wall, while only 11% of Gold Party constituents felt the same [15]. To construct the value functions, it is assumed that full 1150-mile construction of border wall equates to 82% Gold Party constituent satisfaction and 6% Silver Party constituent satisfaction for the wall. At the same time, 0 miles of constructed border wall equates to 11% Gold Party constituent satisfaction and 84% Silver Party constituent satisfaction for the wall. Assuming a linear function between the maximum and minimum satisfaction values for the wall, this means each mile of wall results in a 0.062% wall satisfaction increase for Gold Party constituents and a 0.066% decrease in wall satisfaction for Silver Party constituents. Thus, the equations that will give a score for how one alternative performs for wall satisfaction are shown by 24 and 25 for the Gold Party and Silver Party respectively.

$$GoldSat_{Wall} = 11 + 0.062Miles_{Wall} \tag{24}$$

$$SilverSat_{Wall} = 84 - 0.066Miles_{Wall} \tag{25}$$

Technology 2 and 3: Aerial and ground-based surveillance

Additional polling shows 91% of Gold Party constituents view increasing security on the U.S. Mexico border as somewhat or very important [120], compared to the 82% who favor a wall [15]. Only 49% of Silver Party Constituents feel increasing security on the U.S. Mexico border is somewhat or very important [120]. However, while 49% of Silver Party Constituents support increased security, only 8% support a wall [15]. It is assumed that 41% additional support for increased security, but not for the wall, transfers to aerial and ground-based surveillance technology for Silver Party Constituents. Similarly, it is assumed the additional 9% of Gold Party Constituents supporting increased security but not favoring a wall reflects support for aerial and ground-based surveillance. These polls also imply that any increase in border security will result in 9% of Gold Party constituents being dissatisfied and 51% of Silver Party Constituents being dissatisfied. With no other data differentiating constituents' opinions on the technologies, the same functions is used for both aerial and ground-based surveillance satisfaction. Again, assuming a linear function connecting the maximum and minimum values, each mile of MQ-9 or IFT funded results in a 0.71% increase in aerial surveillance or ground-based surveillance satisfaction for Gold Party members and a 0.002% decrease for Silver Party members. Equations that will give the score for PA performance for aerial surveillance satisfaction are shown in 27 and 28 for the Gold Party and Silver Party respectively. Similarly, equations that will give the score for PA performance for ground-based surveillance satisfaction are shown in 29 and 30 for the Gold Party and Silver Party respectively.

$$GoldSat_{MQ-9} = 9 + 0.071Miles_{MQ-9} \tag{27}$$

$$SilverSat_{MQ-9} = 51 - 0.002Miles_{MQ-9} \tag{28}$$

$$GoldSat_{IFT} = 9 + 0.071Miles_{IFT} \tag{29}$$

$$SilverSat_{IFT} = 51 - 0.002Miles_{IFT} \tag{30}$$

Party specific constituent satisfaction can be calculated by taking an average of the technology satisfaction scores from each of the 3 technologies. The equation that will give a score for PA performance for Gold Party satisfaction is shown in 31. The equation that will give a score for PA performance for Silver Party satisfaction is shown in 32.

$$(31) \quad GoldSat_{PA} = \frac{GoldSat_{Wall} + GoldSat_{MQ-9} + GoldSat_{IFT}}{3}$$

$$(32) \quad SilverSat_{PA} = \frac{SilverSat_{Wall} + SilverSat_{MQ-9} + SilverSat_{IFT}}{3}$$

Finally, because constituencies are comprised of members of both parties, DMs must consider how their decision affects the satisfaction for constituents not of their party as well as constituents of their own party. The overall constituent satisfaction can be calculated as a weighted average based on the percent makeup of a DM's constituency. For example, if a DM has a constituency with 45% Gold Party members and 55% Silver Party members, the overall constituent satisfaction score is calculated by multiplying 45% with the Gold Party PA satisfaction score and adding the answer to 55% multiplied with the Silver Party PA satisfaction score. The equation that will give you a score for overall constituent satisfaction is shown in 33.

$$(33) \qquad ConstSat_{PA} = PercentGold(GoldSat_{PA}) + PercentSilver(SilverSat_{PA})$$

The $ConstSat_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{1,j}$ variable in the constituent satisfaction SAVF shown in 16.

4.5.2 Scoring PAs for Apprehension Capability

Apprehension rates are a well tracked CBP statistic with information detailed by country of origin and sector of capture [16]. Given that the three technologies being considered are already deployed at different parts of the SWB, it was determined that the expected apprehension rate for further system deployment would match that of existing areas. Government

Accountability Office (GAO) and OIG reports provide insight into apprehension rates where the three technologies are currently in use. The average apprehension rate for areas on the SWB with pedestrian fencing is 61.5% [125]. Few apprehensions are credited to aerial surveillance technology. In sectors where the metric is tracked, records indicate only around 1% of apprehensions are attributed to UAS assistance [126]. The Tucson sector is the only CBP sector where the IFT system in currently deployed. In areas without pedestrian fencing, the apprehension rate is 44% [125]. In the absence of any other data, it is assumed that this 44% rate is attributable to the IFT system. With this metric now computed for each technology, PAs can be evaluated based on the average apprehension rate that can be expected across the 1150 miles of unfenced border being considered in this study. The equation for average apprehension rate is shown in 34.

$$(34) \quad AppRate_{PA} = \frac{61.5Miles_{Wall} + 1Miles_{MQ-9} + 44Miles_{IFT} + 0Miles_{No\ Barrier}}{1150\ miles}$$

Note: the constants in the equation for average apprehension rate are based in values that are not mutually exclusive. The expected apprehension rates are based on the conditional probability that illegal crossers are not apprehended as a result of either of the other 2 technologies. This means that if all 3 technologies are deployed over any 1 mile of the SWB, the apprehension rate for that mile would be 106.5%, an impossible value. However, the author elected to still use this equation as no suitable alternate equation could be determined to account for the conditional probability of the apprehension rates. Beyond this factor, no PAs considered in this experiment had average apprehension rates greater than 100%. Finally, as the focus of this study and purpose of the toy model is to demonstrate the methodology, and not to solve the border security dispute, this equation was determined to be adequate for demonstration purposes.

The $AppRate_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{2,j}$ variable in the apprehension capability SAVF shown in 17.

4.5.3 Scoring PAs for Deterrence Capability

Based on the descriptions in Table 17, each mile secured with a physical wall or fence receives a deterrence score of 4, each mile secured with aerial surveillance receives a score of 1, and each mile secured with ground-based surveillance receives a score of 2. All miles where no technology is deployed receives a deterrence score of 0. The equation for deterrence value is shown in 35.

$$(35) \quad Deterrence_{PA} = 4Miles_{Wall} + 1Miles_{MQ-9} + 2Miles_{IFT} + 0Miles_{No\ Barrier}$$

The $Deterrence_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{3,j}$ variable in the deterrence capability SAVF shown in 18.

4.5.4 Scoring PAs for Acquisition Cost

The equation to calculate the acquisition cost of a PA is straightforward. As PAs are given in terms of dollars funded, acquisition cost for a PA is the sum of the amounts allotted for each technology. The equation for acquisition cost is shown in 36.

$$(36) \qquad AcqCost_{PA} = \$Allotted_{wall} + \$Allotted_{MQ-9} + \$Allotted_{IFT}$$

The $AcqCost_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{4,j}$ variable in the acquisition cost SAVF shown in 19.

4.5.5 Scoring PAs for Sustainment Cost

For the wall, the annual sustainment cost is assumed to be similar to sustainment costs for existing sections of fencing along the SWB. Reports show that it costs approximately $55 million each year to maintain the 654 miles of existing border fence [127]. For a per mile basis, that equals approximately $84,000 per year per mile. For aerial surveillance, OIG reports show the MQ-9 costs $12,255 per flight hour per unit [126]. With 24-hour coverage 365 days per year and a 115-mile route distance to maintain persistent coverage, the sustainment cost of the MQ-9 equals $956,000 per year per mile. Finally, the IFT system currently stretches 53 miles. Reports indicate operation and sustainment costs are approximately $22 million per year [12]. Dividing cost by distance, the ground-based surveillance sustainment cost equals approximately $415,000 per mile per year. The sustainment cost for the PA is the summed product of the sustainment cost

($K/year/mile) for the technologies and the associated miles funded. The equation for sustainment cost is shown in 37.

$$(37)\quad SustCost_{PA} = 84Miles_{Wall} + 956Miles_{MQ-9} + 415Miles_{IFT} + 0Miles_{No\ Barrier}$$

The $SustCost_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{5,j}$ variable in the sustainment cost SAVF shown in 20.

4.5.6 Scoring PAs for Permanent Soil Disruption

Several assumptions were necessary to calculate acreage of permanent soil disruption for each of the technologies. For the wall, it was assumed that for each mile of construction, there would need to be a parallel two-way road for patrols (see Figure 45). The Federal Highway Administration (FHWA) sets regulations stating that rural local roads need to be between 9 and 12 feet per lane for safety accordance [128]. So, with an assumed 1-foot width of the wall and a 20-foot adjacent roadway, each mile of wall equates to 2.5 acres of soil permanently disrupted.

Figure 45: U.S. Mexico Border Fence with Adjacent Road [129]

For the MQ-9, it was assumed that existing airfields and infrastructure are adequate for any additional units procured for deployment. As such, 0 acres of soil are disrupted for each mile of MQ-9 patrol. For the IFT system, the acreage of permanent soil disruption is calculated based on results from a CBP environmental assessment. According to the assessment, the project will have approximately 8.24 acres of permanent impact for all towers constructed. In addition, approximately 204.36 acres of landscape would be permanently destroyed for the construction of new service roads to access the towers [11]. The IFT system currently extend 53 miles along Arizona's Mexico-facing border [110]. From this data, the acreage of permanent soil disrupted is calculated by dividing the sum of acres impacted by the distance covered by the system. This equates to approximately 4.0 acres of soil permanently disrupted per mile of IFT. The equation for acres of permanent soil disruption is shown in 38.

$$(38) \quad SoilDist_{PA} = 2.5Miles_{Wall} + 0Miles_{MQ-9} + 4Miles_{IFT} + 0Miles_{No\ Barrier}$$

The $SoilDist_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{6,j}$ variable in the permanent soil disruption SAVF shown in 21.

4.5.7 Scoring PAs for Greenhouse Gas Emissions

Greenhouse gas emissions are frequently measured in terms of CO2 equivalents. In order to effectively summarize CO2 equivalent emissions, it was necessary to account for emissions both from construction and from operations. In order to make a comparable life-cycle emissions metric, an equal lifespan of 20 years was assumed for all technologies. 20 years is the actual expected lifespan of the MQ-9 according to Department of Defense (DoD) reports [3]. For the wall, reports state that using steel slats will result in 75 million kg of CO2 per mile built or 75000 metric tons (mt) per mile [112]. The MQ-9 can carry 587 gallons of fuel and fly for 27 hours [130]. This equates to burning 21.7 gallons of fuel per hour. Burning aviation gas produces 8.35 kg of CO2 per gallon [131], equaling 181.5 kg of CO2 produced per flight hour. Operating over a 115-mile route, 24 hours per day, 365 days per year over a 20-year lifespan results in 276 mt of CO2 per mile. For the IFT system, construction will produce 20,775 mt of CO2 equivalents and each year of operation will produce 3,181 mt. For the 53-mile expanse and an anticipated 20-

year life, the lifecycle CO2 equivalent emissions for the IFT system are approximately 1600 metric tons per mile. The equation for CO2 equivalent lifecycle emissions is shown in 39.

$$(39)\quad CO2Emit_{PA} = 75000Miles_{Wall} + 276Miles_{MQ-9} + 1600Miles_{IFT} + 0Miles_{No\ Barrier}$$

The $CO2Emit_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{7,j}$ variable in the greenhouse gas emissions SAVF shown in 22.

4.5.8 Scoring PAs for Party Unity

The equation for party unity binary function where PAs receiving party leader support receive a score of 1 and PAs not receiving party leader support receive a score of 0. The equation for party leader support is shown in 40.

$$(40)\qquad PartyLead_{PA} = \begin{cases} 1, & if\ Party\ Leader\ Supports\ PA \\ 0, & otherwise \end{cases}$$

The $PartyLead_{PA}$ value is the variable objective score for the PA. This value is used for the $x_{8,j}$ variable in the party unity SAVF shown in 23.

With 8 distinct, attribute specific, SAVFs defined for each of the 20 DMs in the voting body, and PA scoring for each of objectives established, the next step in this experiment is to assess tradeoffs among the different objectives.

4.6 Tradeoff Assessment-Border Security

For the voting body, DM tradeoffs were simulated by generating weights specific to each attribute. Weights were generated by random values drawn from party specific attribute distributions. In the absence of more detailed information, the author opted to used triangular distributions to represent generic political party weighting of an attribute. For further detail on how the party specific distributions were derived for each attribute, see Appendix II. Table 32 shows the weights assigned to each DM in the voting body for each of the 8 attributes.

Table 32: Decision Maker Weights-Border Security

	Constituent Satisfaction	Average Apprehension Rate	Deterrence Value	Acquisition Cost	Sustainment Cost	Permanent Soil Disruption	CO2 Equivalent Lifecycle Emissions	Party Leader Support
Gold DM #1	0.281	0.134	0.131	0.059	0.069	0.089	0.051	0.186
Gold DM #2	0.313	0.133	0.157	0.051	0.084	0.105	0.055	0.101
Gold DM #3	0.316	0.105	0.161	0.064	0.069	0.089	0.052	0.145
Gold DM #4	0.291	0.117	0.149	0.054	0.071	0.088	0.051	0.178
Gold DM #5	0.326	0.115	0.149	0.076	0.059	0.099	0.057	0.120
Gold DM #6	0.287	0.110	0.139	0.060	0.067	0.088	0.049	0.200
Gold DM #7	0.301	0.104	0.169	0.058	0.074	0.100	0.056	0.138
Gold DM #8	0.270	0.116	0.122	0.059	0.066	0.082	0.048	0.238
Gold DM #9	0.303	0.116	0.140	0.066	0.057	0.092	0.052	0.175
Gold DM #10	0.316	0.134	0.157	0.066	0.072	0.093	0.053	0.110
Silver DM #1	0.251	0.074	0.062	0.093	0.070	0.112	0.145	0.193
Silver DM #2	0.279	0.068	0.052	0.113	0.080	0.119	0.145	0.145
Silver DM #3	0.278	0.063	0.059	0.109	0.083	0.117	0.146	0.145
Silver DM #4	0.288	0.080	0.068	0.105	0.087	0.120	0.156	0.096
Silver DM #5	0.256	0.054	0.073	0.106	0.083	0.110	0.142	0.177
Silver DM #6	0.266	0.059	0.063	0.105	0.066	0.116	0.144	0.181
Silver DM #7	0.287	0.070	0.060	0.112	0.072	0.122	0.152	0.124
Silver DM #8	0.260	0.066	0.059	0.097	0.076	0.114	0.142	0.186
Silver DM #9	0.261	0.065	0.071	0.100	0.084	0.121	0.146	0.152
Silver DM #10	0.261	0.059	0.078	0.081	0.065	0.123	0.151	0.181

With the weights defined for all DMs in the voting body, the overall value functions can be constructed using the additive aggregation technique as mentioned in chapter 3.

4.7 Overall Value Function Aggregation-Border Security

The overall value scores for PAs were evaluated using the equation shown in 41.

$$V_{jk}(x_j, \rho_k) = \sum_{i=1}^{7} w_{ik} v_{ijk}(x_j, \rho_{ik}) + w_{8,k} v_{8,j}(x_j) \tag{41}$$

Where $V_{jk}(x_j, \rho_k)$ is the overall value score of the jth PA for the kth DM in the voting body, $\sum_{i=1}^{7} w_{ik} v_{ijk}(x_j, \rho_{ik})$ is the weighted sum of the first 7 attributes defined using the exponential value function, and $w_{8,k} v_{8,j}(x_j)$ is the weighted value of the party leader support attribute, which was defined with a binary function. With the overall value function defined, the next step is to evaluate the 20 PAs in the scenario for the 20 DMs in the voting body.

4.8 Testing the Model-Border Security

To begin evaluating the PAs, all 20 are assessed using the overall value functions for the party leaders from each political party in the scenario. For the simulated voting body Gold DM #1 and Silver DM #1 were selected as their respective parties. Table 33 shows the results of the initial run.

Table 33: Party Leader Support Identifier Run Results

	Gold Lead		Silver Lead	
Rank	Portfolio	Value	Portfolio	Value
1	4	0.507	1	0.736
2	5	0.505	2	0.727
3	9	0.505	6	0.711
4	10	0.504	16	0.703
5	3	0.487	7	0.702
6	2	0.486	17	0.697
7	8	0.486	11	0.694
8	1	0.483	3	0.68
9	7	0.369	12	0.67
10	6	0.364	8	0.669
11	19	0.362	18	0.664
12	20	0.359	13	0.637
13	14	0.343	4	0.398
14	15	0.336	9	0.367
15	18	0.335	19	0.346
16	13	0.333	5	0.337
17	17	0.33	14	0.316
18	16	0.326	10	0.308
19	12	0.323	20	0.306
20	11	0.318	15	0.278

PA 1 is the status quo PA for the analysis, benchmarking where each DM transitions his or her vote from “No” to “Yes” or vice versa. Party leader results show the Gold Party leader supporting 7 PAs (2, 3, 4, 5, 8, 9, and 10). These PAs received a score of 1 for their party leader support measure when evaluating for Gold Party while the other PAs were given a score of 0. The Silver Party leader, on the other hand, disapproved of all PAs. This is conveyed by assigning PA 1 a value of 1 for its party leader support measure when evaluating for Silver Party members. Table 34 shows all 20 PAs from Table 15 with the objective scores. Table 35 shows the percent composition of members from each party for each of the DMs' constituencies as required in the equation shown in 33 to calculate constituent satisfaction. The metrics for constituent satisfaction are broken down by party. The metrics for party leader support are also separated by party.

Table 34: SWB Portfolio Alternatives by Value Measure Metrics

Portfolios	**Silver Satisfaction (%)**	**Gold Satisfaction (%)**	**Average Apprehension Rate (%)**	**Deterrence Value**	**Acquisition Cost ($B)**	**Sustainment Cost ($K/yr)**	**Permanent Soil Disruption (Acres)**	**CO2 Equivalent Lifecycle Emissions (Mmt)**	**Silver Party Leader Support**	**Gold Party Leader Support**
Portfolio Alternative 1	62.00	9.67	0.00	0.00	0.00	0.00	0.00	0	1.00	0.00
Portfolio Alternative 2	60.38	11.19	3.94	294.40	1.60	6.18	184.00	5.52	0.00	1.00
Portfolio Alternative 3	56.23	15.09	14.02	1048.80	5.70	22.02	655.50	19.67	0.00	1.00
Portfolio Alternative 4	38.72	31.53	56.58	4232.00	23.00	88.87	2645.00	79.35	0.00	1.00
Portfolio Alternative 5	36.70	33.43	61.50	4600.00	25.00	96.60	2875.00	86.25	0.00	1.00
Portfolio Alternative 6	61.95	11.52	3.00	156.88	0.18	32.55	313.77	0.13	0.00	0.00
Portfolio Alternative 7	60.33	13.04	6.94	451.28	1.78	38.74	497.77	5.65	0.00	0.00
Portfolio Alternative 8	56.18	16.94	17.02	1205.68	5.88	54.58	969.27	19.79	0.00	1.00
Portfolio Alternative 9	38.67	33.39	59.58	4388.88	23.18	121.43	2958.77	79.48	0.00	1.00
Portfolio Alternative 10	36.65	35.29	64.50	4756.88	25.18	129.15	3188.77	86.38	0.00	1.00
Portfolio Alternative 11	61.82	15.97	3.16	344.83	0.37	212.23	313.77	0.18	0.00	0.00
Portfolio Alternative 12	60.20	17.49	7.10	639.23	1.97	218.41	497.77	5.7	0.00	0.00
Portfolio Alternative 13	56.05	21.39	17.19	1393.63	6.07	234.25	969.27	19.84	0.00	0.00
Portfolio Alternative 14	38.55	37.84	59.74	4576.83	23.37	301.10	2958.77	79.53	0.00	0.00
Portfolio Alternative 15	36.52	39.74	64.66	4944.83	25.37	308.83	3188.77	86.43	0.00	0.00
Portfolio Alternative 16	61.87	14.11	0.16	187.94	0.18	179.67	0.00	0.05	0.00	0.00
Portfolio Alternative 17	60.26	15.64	4.10	482.34	1.78	185.85	184.00	5.57	0.00	0.00
Portfolio Alternative 18	56.11	19.53	14.19	1236.74	5.88	201.70	655.50	19.72	0.00	0.00
Portfolio Alternative 19	38.60	35.98	56.74	4419.94	23.18	268.54	2645.00	79.4	0.00	0.00
Portfolio Alternative 20	36.57	37.88	61.66	4787.94	25.18	276.27	2875.00	86.3	0.00	0.00

Table 35: DM Constituency Political Party Make-ups [132]

Gold Party	**DM #1**	**DM #2**	**DM #3**	**DM #4**	**DM #5**	**DM #6**	**DM #7**	**DM #8**	**DM #9**	**DM #10**
Silver	46%	20%	18%	21%	38%	38%	36%	45%	49%	48%
Gold	54%	80%	82%	79%	62%	62%	64%	55%	51%	52%
Silver Party	**DM #1**	**DM #2**	**DM #3**	**DM #4**	**DM #5**	**DM #6**	**DM #7**	**DM #8**	**DM #9**	**DM #10**
Silver	64%	58%	53%	53%	59%	51%	56%	56%	68%	54%
Gold	36%	42%	47%	47%	41%	49%	44%	44%	32%	46%

4.9 Forecasting Votes-Border Security

Using the data in tables 34 and 35, all PAs were evaluated for the remaining 18 DMs in the voting body according to equation 33. The results of all 20 DM runs are summarized in Table 36 and Table 37. Table 36 contains the results for the Gold Party DMs and Table 37 shows the results for the Silver Party DMs. Note the status quo, PA 1, highlighted in each DM's list, acting as the threshold for an approving vote.

Table 36: SWB MODA Model Results-Gold Party DMs

Gold Party	**DM #1**		**DM #2**		**DM #3**		**DM #4**		**DM #5**		**DM #6**		**DM #7**		**DM #8**		**DM #9**		**DM #10**	
Rank	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value
1	4	0.507	4	0.665	10	0.516	4	0.65	3	0.585	4	0.657	3	0.65	10	0.62	3	0.685	2	0.585
2	5	0.505	5	0.66	5	0.513	9	0.648	8	0.584	9	0.653	8	0.641	5	0.62	8	0.683	3	0.583
3	9	0.505	9	0.654	2	0.511	5	0.643	2	0.577	5	0.653	4	0.637	4	0.617	4	0.68	10	0.574
4	10	0.504	10	0.647	9	0.51	10	0.641	4	0.555	3	0.651	9	0.63	9	0.617	5	0.672	5	0.572
5	3	0.487	8	0.614	4	0.509	8	0.589	9	0.546	10	0.649	5	0.627	3	0.609	9	0.669	8	0.571
6	2	0.486	3	0.607	3	0.509	3	0.589	5	0.544	8	0.649	2	0.625	8	0.608	2	0.668	9	0.567
7	8	0.486	2	0.561	8	0.505	2	0.553	10	0.534	2	0.64	10	0.621	2	0.608	10	0.661	4	0.558
8	1	0.483	19	0.534	1	0.366	19	0.45	7	0.458	7	0.439	18	0.484	7	0.37	7	0.43	1	0.554
9	7	0.369	20	0.528	6	0.362	14	0.447	6	0.454	19	0.437	13	0.481	1	0.37	6	0.422	6	0.461
10	6	0.364	14	0.52	7	0.362	20	0.442	1	0.452	1	0.435	7	0.479	6	0.37	13	0.422	7	0.454
11	19	0.362	15	0.513	15	0.357	15	0.439	18	0.452	6	0.434	19	0.475	20	0.362	1	0.421	16	0.429
12	20	0.359	13	0.496	20	0.355	18	0.395	13	0.451	20	0.433	14	0.473	16	0.36	18	0.42	17	0.429
13	14	0.343	18	0.492	16	0.354	13	0.394	12	0.445	14	0.433	1	0.472	17	0.36	19	0.419	11	0.42
14	15	0.336	7	0.473	17	0.352	7	0.375	17	0.445	15	0.43	20	0.467	19	0.36	20	0.412	12	0.418
15	18	0.335	12	0.463	19	0.35	17	0.361	11	0.442	18	0.428	6	0.465	18	0.359	14	0.412	18	0.416
16	13	0.333	17	0.454	18	0.349	12	0.36	16	0.441	13	0.426	15	0.465	11	0.356	12	0.406	20	0.406
17	17	0.33	6	0.453	14	0.349	6	0.359	19	0.418	17	0.417	17	0.46	12	0.356	15	0.404	15	0.393
18	16	0.326	11	0.447	11	0.347	1	0.358	14	0.409	12	0.416	12	0.458	15	0.356	17	0.402	13	0.38
19	12	0.323	1	0.437	12	0.346	16	0.345	20	0.409	16	0.412	16	0.446	13	0.355	11	0.397	19	0.378
20	11	0.318	16	0.434	13	0.343	11	0.345	15	0.396	11	0.411	11	0.445	14	0.354	16	0.392	14	0.364

Table 37: SWB MODA Model Results-Silver Party DMs

Silver Party	DM #1		DM #2		DM #3		DM #4		DM #5		DM #6		DM #7		DM #8		DM #9		DM #10	
Rank	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value	PA	Value
1	1	0.56	1	0.759	1	0.744	1	0.701	1	0.758	1	0.765	1	0.813	1	0.797	1	0.742	1	0.767
2	2	0.548	6	0.6	2	0.59	6	0.596	6	0.574	2	0.578	2	0.684	6	0.592	2	0.583	2	0.576
3	6	0.544	2	0.598	6	0.589	2	0.594	2	0.564	6	0.573	6	0.681	2	0.585	6	0.579	6	0.573
4	16	0.542	16	0.595	7	0.58	7	0.585	16	0.562	7	0.567	7	0.676	7	0.571	7	0.57	7	0.564
5	7	0.534	7	0.584	16	0.573	3	0.568	7	0.557	3	0.56	3	0.668	16	0.567	3	0.559	16	0.561
6	17	0.53	17	0.577	3	0.564	16	0.566	11	0.551	8	0.548	16	0.66	11	0.556	8	0.546	17	0.551
7	11	0.524	11	0.576	17	0.564	8	0.558	17	0.544	16	0.547	8	0.659	17	0.546	16	0.541	3	0.55
8	3	0.521	12	0.559	11	0.56	11	0.558	12	0.533	17	0.542	17	0.655	3	0.539	11	0.536	11	0.547
9	12	0.513	3	0.556	8	0.554	17	0.556	3	0.52	11	0.54	11	0.652	12	0.535	17	0.534	12	0.538
10	8	0.509	8	0.543	12	0.551	12	0.547	8	0.512	12	0.535	12	0.647	8	0.525	12	0.528	8	0.538
11	18	0.502	18	0.534	18	0.531	18	0.53	18	0.498	18	0.526	18	0.639	18	0.501	18	0.513	18	0.525
12	13	0.486	13	0.516	13	0.523	13	0.52	13	0.486	13	0.519	13	0.629	13	0.49	13	0.506	13	0.512
13	4	0.371	4	0.356	4	0.378	4	0.4	4	0.347	4	0.386	4	0.497	4	0.397	4	0.387	4	0.378
14	9	0.366	9	0.349	9	0.366	9	0.383	9	0.337	9	0.369	9	0.482	9	0.383	9	0.365	9	0.368
15	19	0.345	19	0.325	5	0.344	19	0.364	5	0.329	19	0.362	19	0.466	5	0.38	5	0.355	19	0.353
16	5	0.336	5	0.325	19	0.343	5	0.358	10	0.318	14	0.349	5	0.46	10	0.366	19	0.351	5	0.346
17	14	0.335	10	0.318	10	0.331	14	0.348	19	0.316	5	0.345	14	0.45	19	0.364	14	0.335	14	0.342
18	10	0.332	14	0.311	14	0.327	10	0.34	14	0.298	10	0.327	10	0.443	14	0.353	10	0.332	10	0.336
19	20	0.309	20	0.293	20	0.308	20	0.322	20	0.297	20	0.322	20	0.428	20	0.348	20	0.32	20	0.321
20	15	0.3	15	0.28	15	0.292	15	0.304	15	0.278	15	0.308	15	0.411	15	0.336	15	0.302	15	0.31

4.10 Analysis-Border Security

Analysis begins by summing the total number of "Yes" and "No" votes each PA received. Although it is not the case for this problem, if any PAs were to receive more than 50% approval, findings can be presented as existing, with a clear recommendation of 1 or several PAs with a reasonable probability of being approved by the voting body. However, when dealing with highly contentious problems such as border security, it may be expected that no single solution will become an obvious best. Had the data produced any PAs approved by the Silver Party DMs, it would also be useful to notate any PAs receiving bipartisan support. Table 38 summarizes the vote totals for each PA in the study.

Table 38: SWB MODA Model Vote Totals

Portfolio Alternative	Yes Votes	No Votes	Bipartisan Support
1	N/A	N/A	N/A
2	10	10	No
3	10	10	No
4	10	10	No
5	10	10	No
6	4	16	No
7	7	13	No
8	10	10	No
9	10	10	No
10	10	10	No
11	1	19	No
12	2	18	No
13	4	16	No
14	3	17	No
15	2	18	No
16	0	20	No
17	2	18	No
18	3	17	No
19	4	16	No
20	2	18	No

None of the PAs were determined to be politically viable according to the original definition. Only 7 PAs of the 20 considered received 10 approving votes from the simulated body. Given that all 10 simulated Silver Party DMs opposed all options brought forward, this means the 7 PAs that received 10 supporting votes all came from the simulated Gold Party DMs. It is also interesting to note that the 7 PAs that received unanimous Gold Party support were the same 7 PAs that received a “Yes” vote during the initial run of party leaders to determine the party leader support value measure. This means that regardless of the other preference parameters, in this instance, no DM voted against a solution supported by their party leader, reinforcing the value of party unity within a voting body. Additional analysis is conducted to see if any further information can be gathered to benefit CBP in the scenario.

4.10.1 Average Rank

In practice, given the results of the model, DMs may seek further understanding from the data. In this scenario, it is plausible that Gold Party DMs would seek to sway any Silver Party DMs to vote for one or more of the 7 PAs that received 10 Gold Party votes. The question arises, which PA(s) should be used to try and sway an opposing party DM? The average rank of the PAs provides further insight to answer this question. Table 39 contains the average rank of PAs among Gold Party DMs, Silver Party DMs, and the average rank of PAs for all DMs in the voting body, regardless of party affiliation. Again, the status quo PA is annotated in the tables to show the threshold for an approving vote.

Table 39: Average PA Rankings Among Gold Party, Silver Party, and Collective DMs

Gold Party Summary		Silver Party Summary		Voting Body Summary	
PA	Average Rank	PA	Average Rank	PA	Average Rank
4	2.9	1	1	2	3.85
5	3.3	2	2.4	3	5.2
3	3.7	6	2.6	1	6.2
9	3.8	7	4.3	8	6.6
10	4.3	16	5.3	6	7.1
8	4.7	3	6.7	7	7.1
2	5.3	17	7.3	4	7.95
7	9.9	11	7.6	9	8.9
1	11.4	8	8.5	5	9.5
6	11.6	12	9.3	10	10.85
19	12.5	18	11	16	11
20	12.9	13	12	17	11.3
18	13.2	4	13	18	12.1
13	14.5	9	14	11	12.75
14	14.7	19	15.6	12	12.9
15	14.9	5	15.7	13	13.25
17	15.3	14	17.3	19	14.05
12	16.5	10	17.4	20	15.95
16	16.7	20	19	14	16
11	17.9	15	20	15	17.45

The Gold Party list contains 8 PAs with higher average rankings than PA 1. PA 7 has an average rank of 9.9, compared to 11.4 for PA 1, despite only receiving 7 Gold Party votes, according to the model results. In practice, Gold Party members may be inclined to discount this PA from consideration because it would require persuading 4 additional DMs (Gold or Silver Party) to change their vote, rather than a single Silver Party, as is the case with the other 7 PAs. The Silver Party list indicates that, while no PAs have a greater value score rank greater than PA 1, PAs 2, 3, 7, and 8 all have relatively good average ranks, indicating that several Silver Party DMs could have a favorable view of the PAs, despite not preferring any over the option to keep the status quo through PA 1. Finally, the list for the entire voting body shows PAs 2 and 3 have average ranks better than that of PA 1. Based on this average rank information, a Gold Party DM seeking to sway a Silver Party DM could narrow the list of PAs to push on congressional colleagues from 7 PAs to 4, 3, or even 2, depending on personal preference.

4.10.2 What-If Analysis

Beyond knowing which PAs to pursue further, it may also be beneficial for a Gold Party DM to be able to identify whom among the Silver Party DMs would be more likely to break from the party and vote in favor of any of the other PAs. Going one step beyond identifying the individual(s) more likely to change their vote, a series of what-if analyses on the weights DMs assign to objectives provide insight into which arenas of thought those individuals may be more responsive. To highlight this point, consider a scenario where a Gold Party DM wants to persuade a Silver Party DM to consider different PAs. Based on the functions in the value model, the Gold Party can appeal to the DM in three different ways: highlighting desires of constituents in the DMs home district, appealing to the DMs own personal ideology, or encouraging rebellion from party leadership. Sensitivity analyses for the Silver Party DMs convey information that may help the Gold Party DMs decide which position to take. Figures 46-48 show sensitivity analyses, applied at the fundamental objective level of the value hierarchy, for Silver Party DM #2.

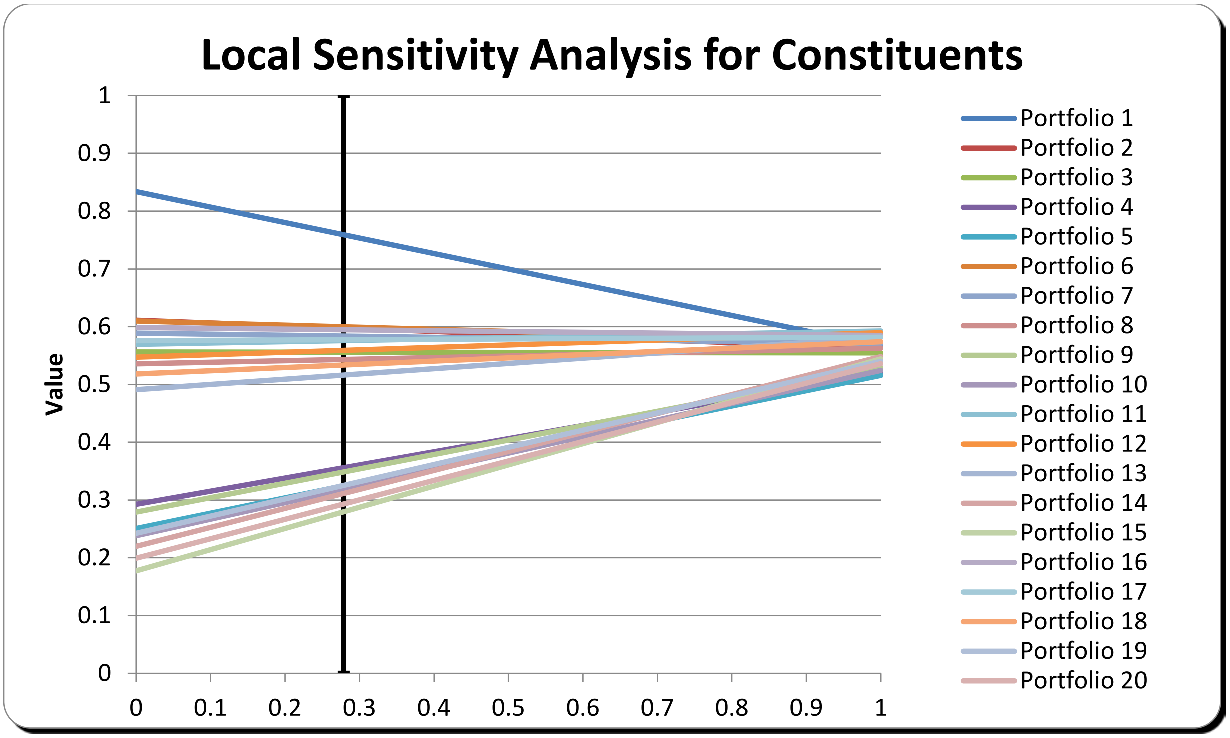


Figure 46: Silver Party DM #2 Sensitivity Analysis: Constituent Satisfaction

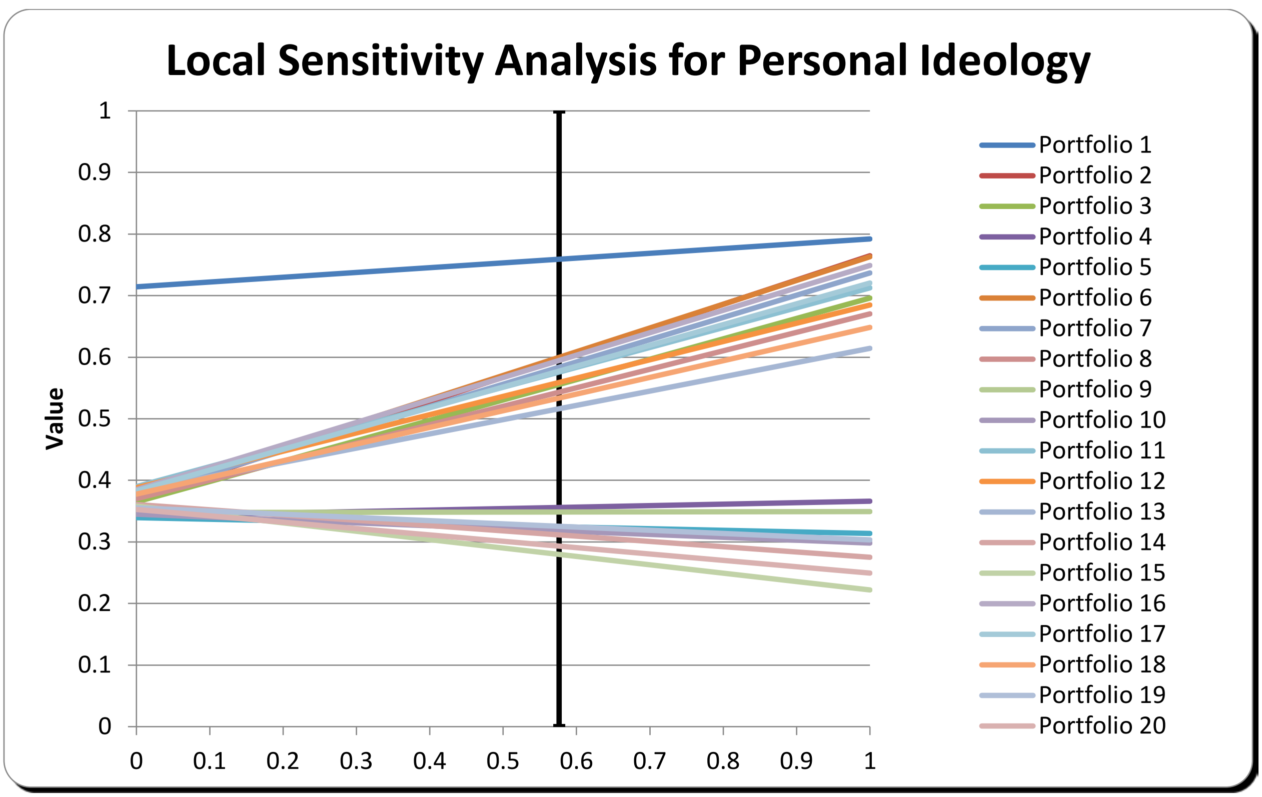


Figure 47: Silver Party DM #2 Sensitivity Analysis: Adopt Best SWB Funding Strategy for Personal Ideology

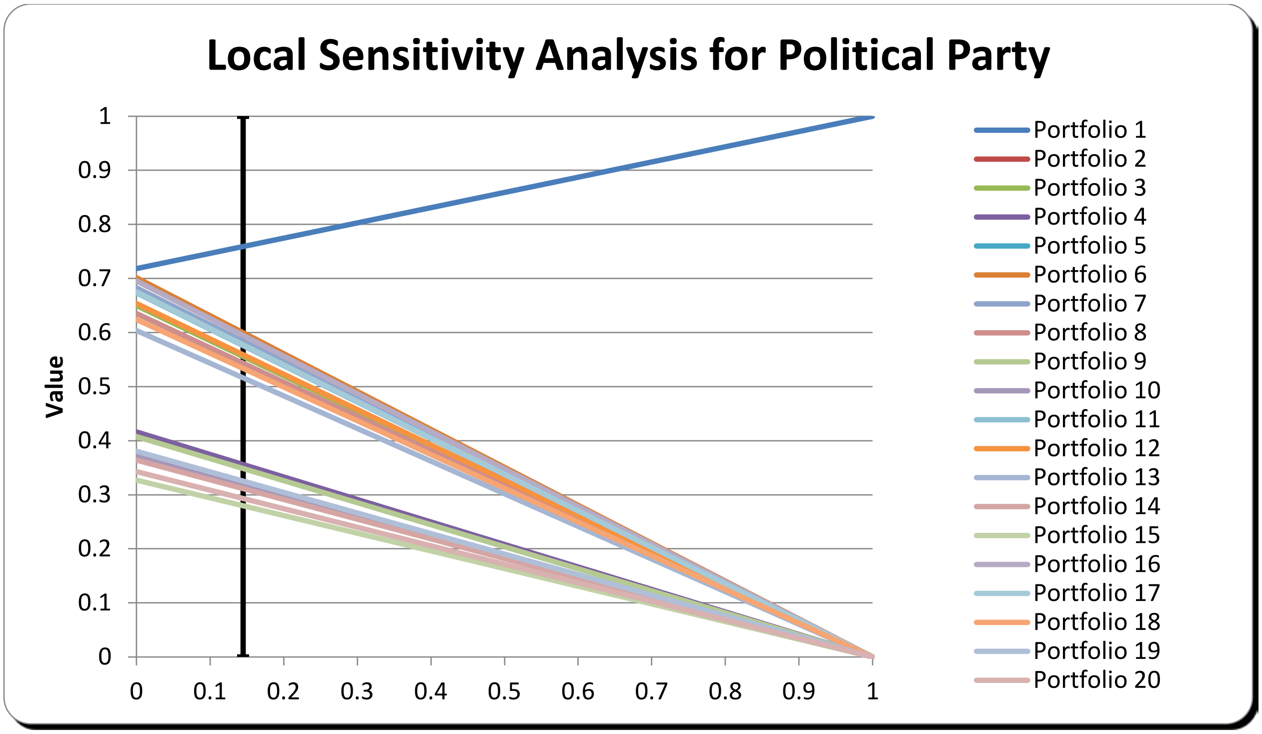


Figure 48: Silver Party DM #2 Sensitivity Analysis: Political Party Unity

PA 1 is the dominant solution regardless of weight assigned to personal ideology or political party unity. This is identical for all 10 Silver Party DMs in the analysis (see Appendix 3). The only area any potential change of vote was evident was with DMs constituencies. Based on these sensitivity analyses, Gold Party DMs may be inclined to target those Silver Party DMs more likely to be pressured by their constituencies. Examples of these could include those DMs nearing a re-election effort and/or from consistently competitive districts [27], or in this scenario, DMs from a U.S.-Mexico border state where constituents may feel they have more at stake for this issue.

Furthermore, in a real-life scenario, Gold Party DMs could go DM-by-DM and analyze compounding effects of addressing certain issues. For example, now looking at Silver Party DM #4, the DM must weight constituent satisfaction at 96% before any of the 8 PAs from the Republican average rank list rise above that of PA 1. At the same time, if that same Silver Party

DM was disenchanted with party leadership, thus placing a weight of 0% on party leader support, the weighting percent for the constituent function needed before a PA from the Gold Party list appears drops from 96% to 84%. For further insight, see Appendix III for all sensitivity analysis graphs for functions and objectives for all 20 DMs in the voting body.

4.10.3 Conclusion-Border Security

Ultimately, the information that becomes available after performing a MODA for each DM in a voting body opens a near infinite realm of analysis options. As demonstrated in this section, those insights may include identifying those alternatives that receive support among a majority or near majority of DMs, followed by the ability to identify from the remaining DMs who has the potential to be persuaded to change their votes. In addition to identifying persuadable DMs, sensitivity and what-if analyses can indicate how these DMs might respond to different messaging. All the information from the results and analysis sections would provide additional points of reference for CBP. Thus, aiding CBP in its decision about which funding proposal to submit to the voting body.

4.11 Methodology Conclusion

This chapter has demonstrated the applicability of the methodology from chapter 3. We believe this chapter has successfully demonstrated the ability of this methodology to forecast votes from a voting body for an array of different alternatives. The status quo alternative acted as an objective threshold for determining alternatives receiving an approving vote from a decision maker. This chapter demonstrated capability of the methodology in dealing with multiple decision makers both with party specific preferences and individual priorities. Analysis of experiment results unveiled the potential of the methodology to assess decision makers on an individual level, thereby providing insight into decision makers whom may be persuadable. Not only did analysis show the potential to identify which decision makers could be persuadable, but also identified which alternatives and which arenas of thought may be most successful in the persuasion effort. Based on this initial assessment of the methodology, we believe there is ample room for further research for real-world application of the methodology.

4.12 Conclusion

This chapter detailed a MODA for the United States-Mexico border security debate that resulted in the longest government shutdown in U.S. history. Using published government reports, scholarly articles, and recent data published from polling centers and news media, the study developed a value hierarchy to evaluate 20 alternatives developed from 5 proposals brought before Congress, or the public, at or after the time of the shutdown. Using public polling data to simulate 10 DMs from opposing political parties, the study established a novel methodology for an objective voting criterion by which to compare alternatives. Upon evaluation of all alternatives by all DMs in the voting body, analysis was conducted to determine which alternatives had certain level of baseline support, which DMs may have the best potential of being persuaded to change votes, and which messaging may be most effective in the persuasion effort.

Chapter 5: Conclusion

5.1 Introduction

This chapter provides a summary of this research beginning with a chapter review, summary of findings, a list of assumptions, and recommendations for future research.

5.2 Chapter Review

The introduction to this research in Chapter 1 explained the December 2018 U.S. government shutdown, which presented a decision problem that inspired this work. In the introduction, the objective of this research was set forth as a goal to theorize and test a repeatable process that can be used to assess the political viability of an alternative that is to be submitted to a voting body for approval. It also set forth the research question, "How can a multi-objective decision analysis framework be used to predict the results from a voting body when assessing multiple proposals?"

Chapter 2 consisted of a literature review detailing the U.S. legislative process, past government shutdowns, a history on USBP, enforcement efforts on the United States SWB, and a breakdown of decision analysis into decision problem types.

Chapter 3 set forth the methodology for this research beginning with constructing valid value hierarchies to reflect voting body objectives and turning them into operational frameworks by determining attributes, defining SAVFs, assessing tradeoffs, and aggregating scores to determine an overall value for an alternative. Chapter 3 also detailed the novel technique proposed to forecast votes on multiple alternatives for all DMs in a voting body.

Chapter 4 applied the processes and techniques described in the methodology in an experiment with a simulated voting body of DMs for the border security problems and drew basic conclusions about both the experiment results and the methodology as a new process.

5.3 Summary of Findings

This research was able to successfully theorize and test a multi-objective decision analysis framework for a complex decision problem and forecast votes, thus, assessing political viability for multiple alternatives. This met the research objective and answered the research question posed in the introduction. This methodology was determined to be repeatable based on the example of the city tax policy in chapter 3 in conjunction with the more in-depth experiment for border security run in Chapter 4.

The experiment results for the border security problem resulted in a grid lock scenario where no alternatives were approved by a majority of the voting body. This provided opportunity for further analysis by assessing the average rank of alternatives among political parties and the entire voting body. Determining the average rank of each alternative identified, which while still opposed, were less objectionable to DMs in the voting body whom may be persuaded to change votes. Beyond average rank, what-if analysis also revealed potential to assess individual DMs and identify which alternatives those DMs may be more inclined to accept and which objectives those seeking to persuade them should emphasize when doing so.

Experiment results led to the general conclusions for the methodology, which is that vote forecasting can be done using a multi-objective decision analysis framework, results can be used to assess the political viability of multiple alternatives, and the methodology shows great potential for additional insights into decision maker behavior. However, this novel technique for vote forecasting is in its infancy. There were limitations to the research and assumptions for the methodology. As such, there are several areas for future research necessary for this technique to mature and prove effective in real-life decision problems.

5.4 Assumptions

The metric for apprehension rate, acquisition and sustainment costs, permanent soil disruption, and CO2 equivalent emissions are assumed to be reliable for purposes of the experiment. In addition, it is assumed that a simulated voting body, constructed based on opinion polls of U.S. citizens, is an adequate substitute for real decision makers in a voting body. However, if these assumptions were proven false, it would not invalidate the conclusions drawn about the vote forecasting methodology. Any discrepancies in model construction speak to discrediting the findings of the model. If discrepancies were corrected, the process used for vote forecasting would still be equally effective.

There were 2 key assumptions necessary, however, for the vote forecasting methodology to be effective in predicting votes for a complex decision problem. Those assumptions are as follows:

1. All decision makers in the voting body have a working knowledge of the issue under consideration such that they are able to provide reliable input data about their personal preferences. Research shows that given the demand on elected officials time between campaigning and the plethora of complex problems they are facing as decision makers, it may not be possible for these decision makers to be educated on every topic where this methodology could be used [27].
2. Decision makers base votes solely on whether or not they, according to personal preferences, prefer an alternative over the current situation, or status quo. No votes in favor of a proposal will not be denied because they are good but “not doing enough,” because of spitefulness or disdain for another decision maker or an opposing political party, nor are any votes in favor of a proposal given out of political favor to another decision maker in the voting body [21].

5.5 Recommendations for Future Work

Based on the findings of this research there are 3 recommendations we believe will further this work and lead to a maturation of the vote forecasting process, such that it becomes a useable framework for real-life decision problems. These recommendations are to build up the software, use Monte Carlo simulation to develop probabilities of approval for each alternative, and test the methodology using real decision makers.

The first recommendation is to develop a software platform where users can construct their value hierarchy, identify attributes, build SAVFs and apply tradeoff weights for all DMs in a voting body at once. Current software can run a complete analysis for a single DM, but individual preferences must be adjusted for each DM in the voting body. This makes it incredibly time consuming to run a large experiment with more than a small number of DMs. In addition, developing the software for multiple decision maker analysis enables the second recommendation.

The second recommendation is to use Monte Carlo simulation to assess the effects of varying mid-values and weights for each DM. Running such analyses could produce probabilities of acceptance for each alternative, rather than a single reference point as is the case with the current methodology.

The final recommendation is to find small scale, real-life scenarios to test the vote forecasting methodology. Using real decision maker objective and preference data may reveal further limitations or additional uses for the new approach.

5.6 Summary

Many complex decision problems in today's world involve voting bodies acting as the final decision authority. Little research has been done to include voting as the decision process when attempting to solve these problems using decision analysis techniques. This research successfully theorized and tested a multi-objective decision analysis framework to predict results from a voting body when assessing multiple proposals. The test used a simulated voting body addressing the problem of border security between the United States and Mexico. The methodology showed positive results and an ability to forecast votes from a voting body. As such, further study of the proposed methodology is recommended.

Appendix I: Miles of Coverage Metric Calculations

This appendix describes the derivations of the coverage metric for the 3 technologies comprising each of the 20 PAs considered in the experiment. The 3 technologies include a physical barrier, aerial surveillance, and ground-based surveillance. The coverage metric was necessary to determine how many miles of each technology could be constructed or deployed from the dollars allotted from each of the PAs.

The Wall: Several economic analyses have been conducted to determine how much it would cost to construct the wall, but estimates settle around $25 billion for the 1150 miles of unfenced area along the SWB [14]. This was the same amount requested in the bill proposed just prior to the 2018-2019 government shutdown [9]. Therefore, coverage for the wall can be calculated by dividing the distance in miles by the expected acquisition cost. The equation for miles of wall coverage is shown in 42.

$$(42) \qquad Coverage_{wall} = \frac{Distance}{Cost} = \frac{1150\,mi}{\$25B} = 46\,\frac{mi}{\$B}$$

Figure 49: Section of Bollard Barrier Steel Slated Fence currently in use along the SWB [111]

Aerial Surveillance: Coverage for aerial surveillance was among the most difficult metrics to derive. To begin, it was assumed that to provide persistent, mile-by-mile coverage comparable to the other two technologies, it would require visual coverage of the same location at least once per hour. In addition, in order to ensure continuous coverage, drone routes must be manned 24 hours per day [126]. To meet this criterion, account for refueling and maintenance, and to extend the life of each drone, it is assumed that each vehicle will operate on the current Office of the Inspector General (OIG) estimates of a 15% duty cycle or just over 3.5 hours per day. This means it will take 7 drones to maintain complete coverage over a given route. The unit cost of an MQ-9 is $16M [116]. It has an average cruise speed of 230 mph [116]. At 230 mph, Predator B can cover 115 miles before turning around and revisiting the route's starting location within the one-hour time limit required to provide persistent coverage as it has been defined. Using this information, coverage can be calculated by dividing the distance of the drone route by the product of the unit cost and the units required per route. The equation to calculate miles of aerial surveillance coverage is shown in 43

$$(43) \quad Coverage_{AS} = \frac{115\ \frac{mi}{Route}}{7\frac{units}{Route} * 0.016\frac{\$B}{Craft}} = 1027\frac{mi}{\$B}$$

Figure 50: Fleet of 3 MQ-9 Predator B UAS operated by CBP [113]

<u>Ground-Based Surveillance:</u> Persistent ground-based surveillance was interpreted as fixed ground sensors that provide 24/7 surveillance. The integrated fixed towers system (IFT) spans 53 miles of CBP's Tucson sector. That expanse had an approximate procurement cost of $123M [110]. Coverage for the IFT system can be calculated by dividing the distance of the existing infrastructure by the procurement cost. The equation to calculate ground-based surveillance coverage is shown in 44.

$$(44) \quad Coverage_{GBS} = \frac{Distance}{Cost} = \frac{53\ mi}{\$0.123B} = 431\frac{mi}{\$B}$$

Figure 51: Constructed Tower and Sensors for the Integrated Fixed Towers (IFT) System [114]

No Barrier: Areas outside of coverage from a PA will be considered to have no barrier. There is nothing detecting, tracking, preventing persons crossing areas with no barrier. Thus, the resulting coverage for no barrier is 0 miles per billion dollars spent. The conversion is shown in 45.

$$(45) \qquad Coverage_{NoBarrier} = 0\frac{mi}{\$B}$$

With the coverage for each technology defined, it is possible to calculate the miles of coverage for each technology. The equations for each technology are shown in 46, 47, 48, and 49.

$$(46) \qquad Miles_{wall} = 46(\$Alloted_{Wall})$$

$$(47) \qquad Miles_{AS} = 1027(\$Alloted_{AS})$$

$$(48) \qquad Miles_{wall} = 431(\$Alloted_{GBS})$$

$$(49) \qquad Miles_{NoBarrier} = Max[1150 - Miles_{wall} - Miles_{AS} - Miles_{GBS}, 0]$$

Appendix II: Decision Maker Weight Distributions

Constructing realistic weights for the attributes required understanding relationships at the fundamental objective level as well as the fundamental objective specification level A political science study about the voting habits of United States Senators found that an average senator, weights his or her voting priorities as follows: constituent satisfaction (mean-26%, max-28%, min-23%), personal ideology (62%, 69%, 52%), and party unity (13%, 25%, 2%) [58]. In the absence of more specific information, these values were used to construct triangular distribution.

Further research was necessary to construct the distributions for the fundamental objective specifications under the personal ideology fundamental objective. The distributions for the 6 personal ideology attributes were derived and generated from public polling conducted by Pew Research Center (PRC) and other outlets. To do so, the attributes were grouped into 3 categories: security, cost, and environmental impact. These categories align with end outcome goals from the affinity diagram in Figure 28 of chapter 4.

i. Security

To generate the security pseudo poll, as it applies to illegal immigration, this study used PRC pieces titled *[Gold Party] and [Silver Party] have very different goals for the nation's immigration policy* [24] and *[Silver Party members] prioritize safe, clean conditions for asylum seekers; [Gold Party members] focus on cutting flow of migrants* [25]. An additional poll from The Hill news organization was used, titled *Poll: Americans want lame-duck Congress to focus on border security, health care* [61]. The polls showed the percent of Silver Party (S) members and Gold Party (G) members saying that a given policy option or priority is very or somewhat important to them. Policy options and priorities included *Reduce number of people coming to U.S. to seek asylum* (S-60%, G-90%), *Build a wall along the U.S.-Mexico border* (S-16%, G-

67%), *Increase deportations of immigrants in U.S. illegally* (S-41%, G-81%), *Establish stricter policies to prevent people from overstaying visas* (S-67%, G-90%), *Congress should focus on border security during the shutdown* (S-10%, G-50%). Using these values, an average (S-39%, G-76%), a maximum (S-67%, G-90%), and minimum (S-10%, G-50%) were calculated to generate triangular distributions describing feelings about maximizing security for each party.

ii. Cost

To generate the minimize cost pseudo poll, the toy model used a different proxy. Rather than determining how much a party is willing or not willing to spend on border enforcement, the toy model calculated the average each party wants to increase spending on other priorities. This pseudo poll was generated using a piece from Pew Research Center titled *Partisans differ on spending for most programs but agree on veteran benefits* [119]. The polls showed the percent of Silver Party members and Gold Party members willing to increase spending for specific priorities. Priorities used in the pseudo poll included *Education* (S-84%, G-56%), *Rebuilding Highways and Bridges* (S-64%, G-57%), *Medicare* (S-68%, G-38%), *Environmental Protection* (S-73%, G-29%), *Healthcare* (S-73%, G-27%), *Scientific Research* (S-62%, G-40%), *Social Security* (S-57%, G-38%), *Assistance to needy in U.S.* (S-62%, G-27%), *Anti-terrorism in the U.S.* (S-30%, G-55%), *Military Defense* (S-26%, G-56%), *Assistance to needy in the world* (S-49%, G-15%), *Assistance to Unemployed* (S-47%, G-10%). Using these values, an average (S-58%, G-37%), a maximum (S-84%, G-57%), and minimum (S-26%, G-10%) were calculated to generate triangular distributions describing feelings about minimizing cost for each party.

iii. Environmental Impact

Unlike the previous 2 groups, the pseudo polls for soil disruption and CO2 emissions were generated separately from the beginning. The study used polls from a PRC piece titled

Millennials in the Gold Party less in favor of expanding fossil fuel use than other Gold Party members [121]. The polls show the percent of Silver Party members who say the government is doing too little on a given environmental priority, and the percent of Gold Party members, in each generational category, claiming the same. In order to determine the strict partisan divide, an average of all Gold Party generational categories was used for the collective. The priorities for soil disruption included in the pseudo poll were *Protect animals and habitats* (S-79%, G-43%), *Protect water quality of lakes/rivers/streams* (S-84%, G-50%), and *Protect open lands in national parks* (S-74%, G-33%). Using these values, an average (S-79%, G-42%), a maximum (S-84%, G-50%), and minimum (S-74%, G-33%) were calculated to generate triangular distributions describing priorities for minimizing permanent soil disruption for each party.

Polls from same PRC piece were used to develop the pseudo polls for the CO2 emissions value measure. The polls capturing this measure asked if voters believe *Government is doing too little to reduce effects of climate change* (S-89%, G-36%), *protect air quality* (S-83%, G-39%), *believe earth is warming mostly due to human activity* (S-75%, G-26%), and *not in favor of expanding use of hydraulic fracturing* (S-75%, G-42%), *coal mining* (S-80%, G-42%), and *offshore oil and gas drilling* (S-78%, G-39%) [121]. These values combine to give an average (S-80%, G-39%), a maximum (S-89%, G-42%), and a minimum (S-75%, G-26%) for the distribution capturing DMs' weighting possibilities for CO2 emissions.

Once determined, the distribution means were combined at the function level and normalized to sum to 1. The maximum and minimum values were then calculated to be proportional to the original value measure distributions. Table 40 shows the final value measure distributions used for each political party's DMs. Figures 52-59 approximate party distribution graphs of DMs that result from random sampling. Dark regions in the center of some graphs indicate overlap preference weighting.

Table 40: Attribute Weight Distribution Parameters by Political Party

	Party	Mean	Maximum	Minimum
Constituent Satisfaction	Silver	27.7%	29.7%	24.7%
	Gold	30.1%	32.1%	27.1%
Apprehension Rate	Silver	6.6%	8.5%	4.7%
	Gold	12.2%	13.9%	9.0%
Deterrence Value	Silver	6.3%	8.0%	4.4%
	Gold	15.1%	17.2%	11.2%
Acquisition Cost	Silver	10.7%	13.5%	7.3%
	Gold	6.1%	7.3%	4.5%
Sustainment Cost	Silver	8.4%	10.6%	5.7%
	Gold	7.2%	8.6%	5.2%
Permanent Soil Disruption	Silver	11.8%	12.3%	11.2%
	Gold	9.0%	9.8%	8.2%
CO2 Equivalent Emissions	Silver	14.6%	15.9%	13.8%
	Gold	5.3%	5.6%	4.7%
Party Leader Support	Silver	13.9%	25.9%	2.9%
	Gold	15.0%	27.0%	4.0%

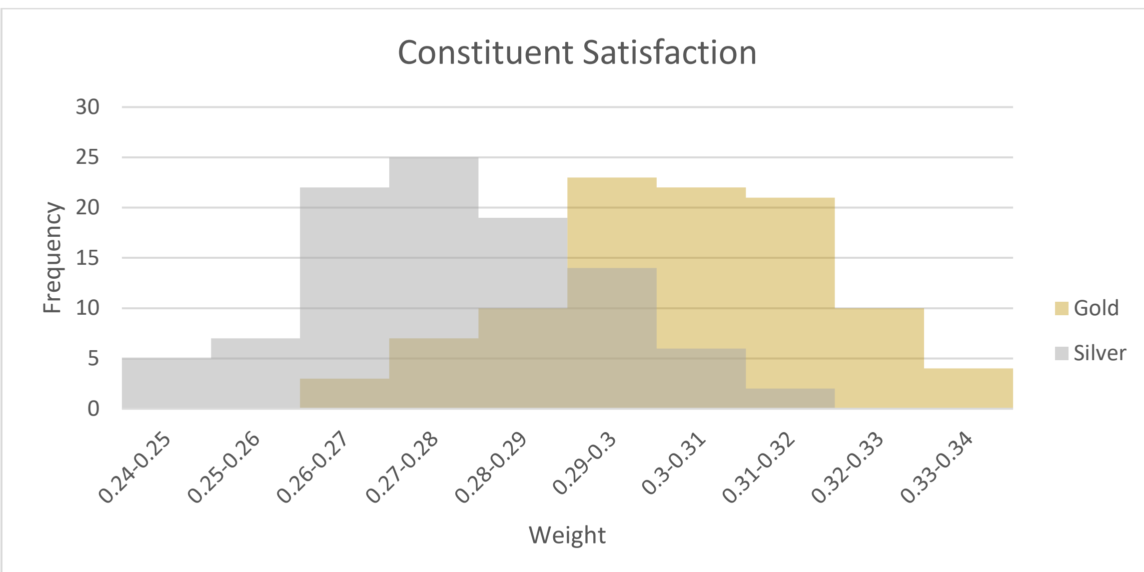


Figure 52: Constituent Satisfaction Weight Distribution by Political Party

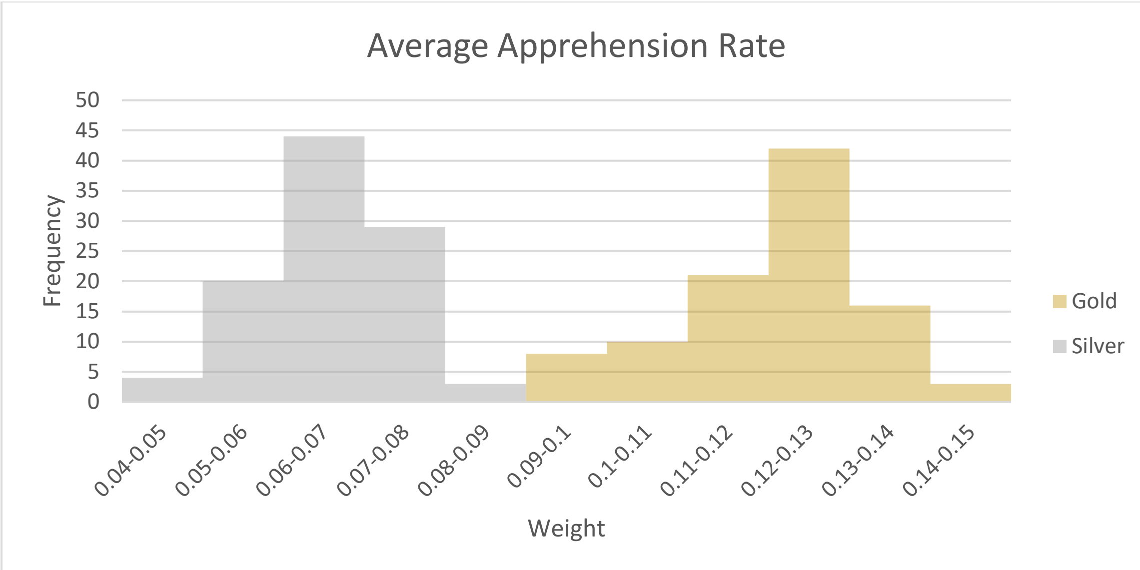


Figure 53: Average Apprehension Rate Weight Distribution by Political Party

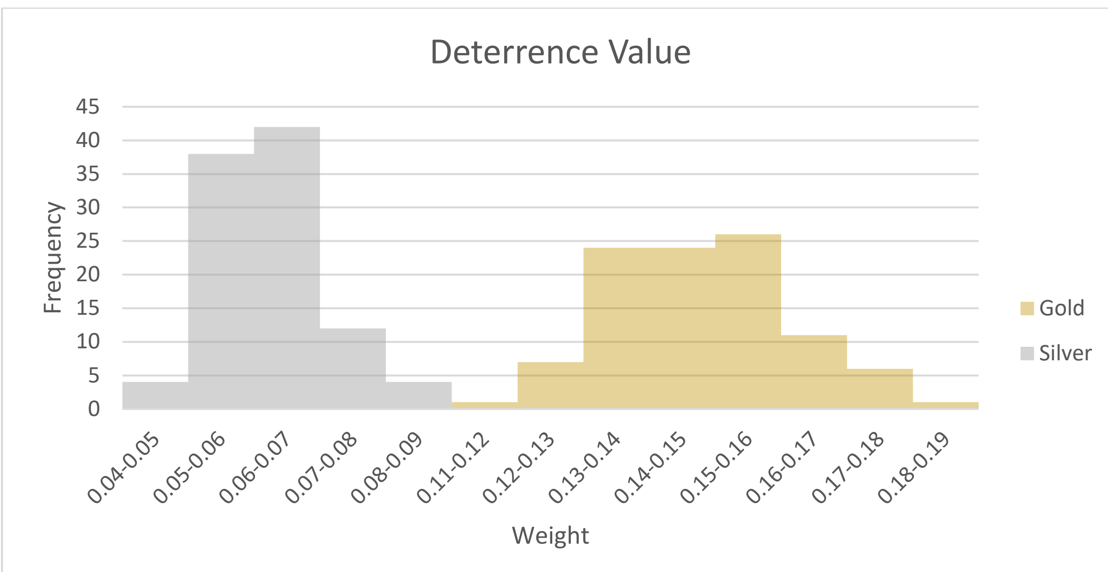


Figure 54: Deterrence Weight Distribution by Political Party

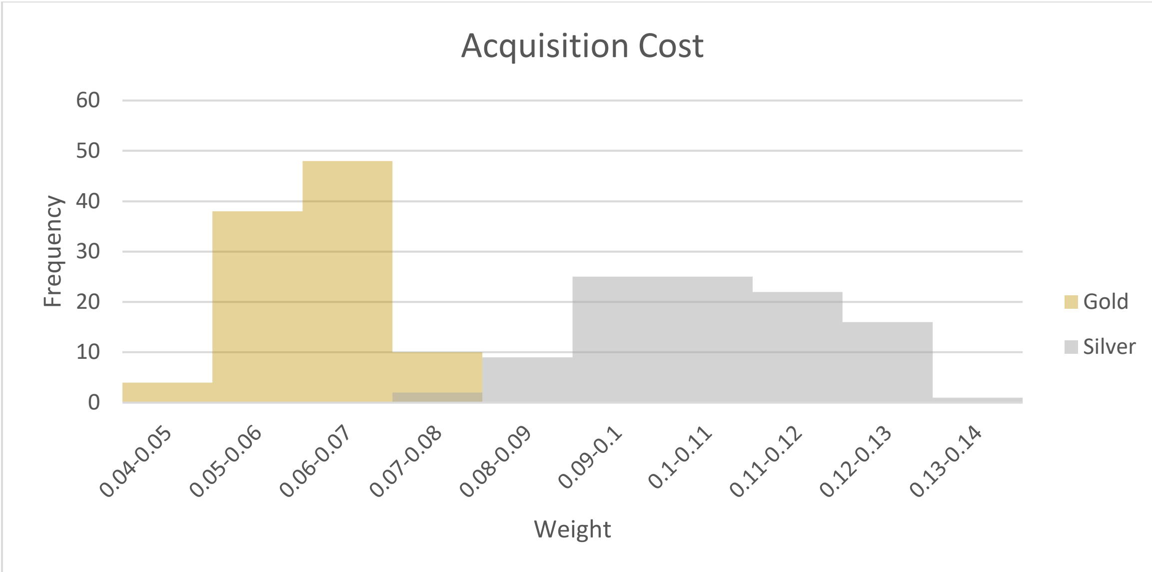


Figure 55: Acquisition Cost Weight Distribution by Political Party

Figure 56: Sustainment Cost Weight Distribution by Political Party

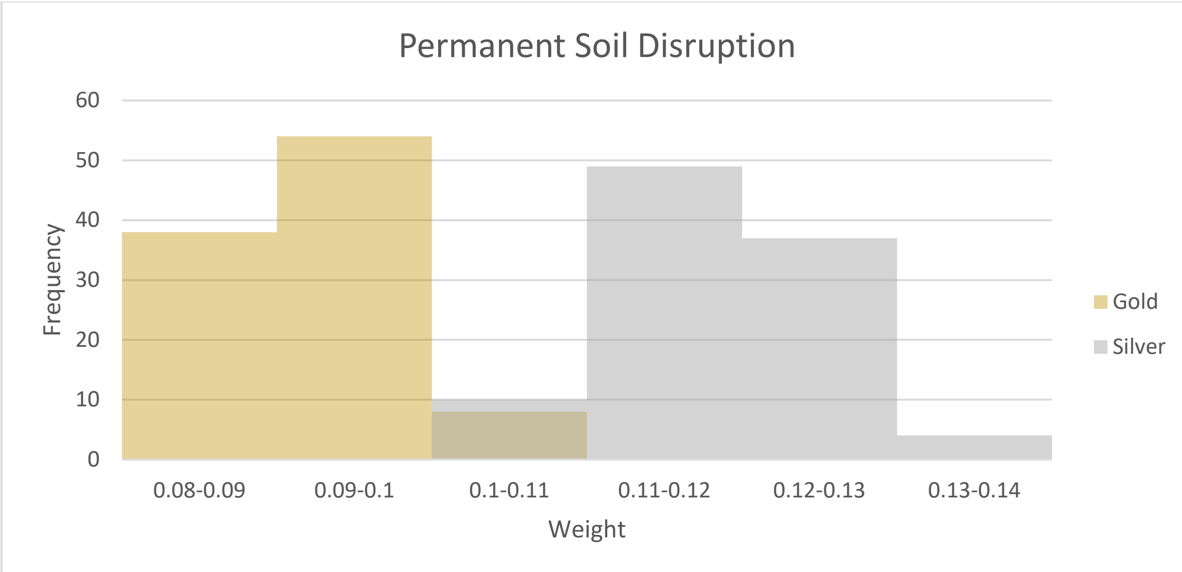


Figure 57: Permanent Soil Disruption Weight Distribution by Political Party

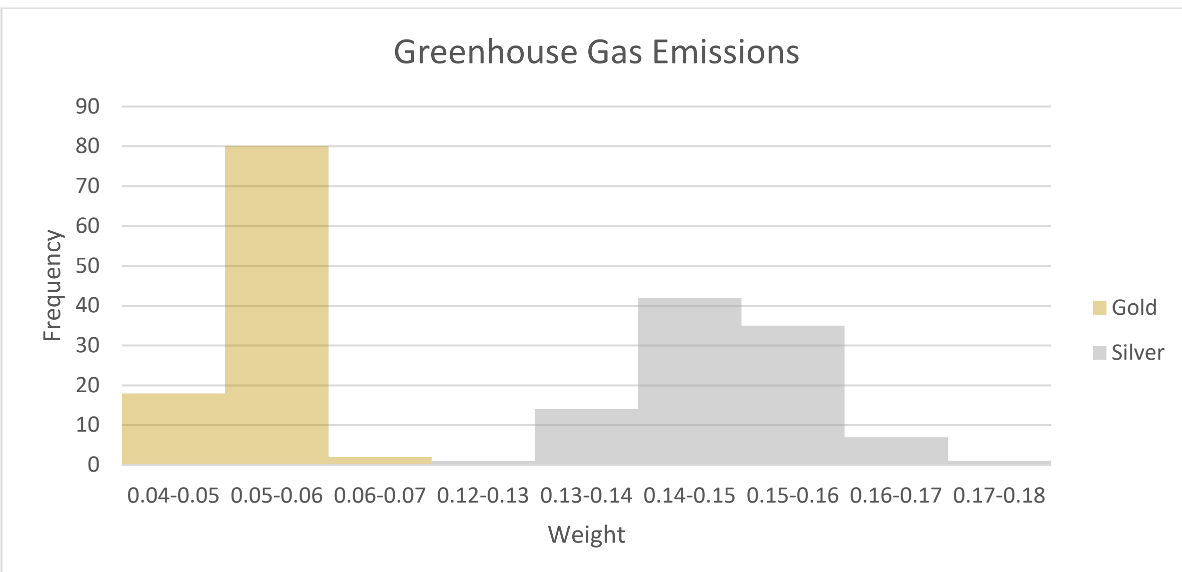


Figure 58: Greenhouse Gas Emissions Weight Distribution by Political Party

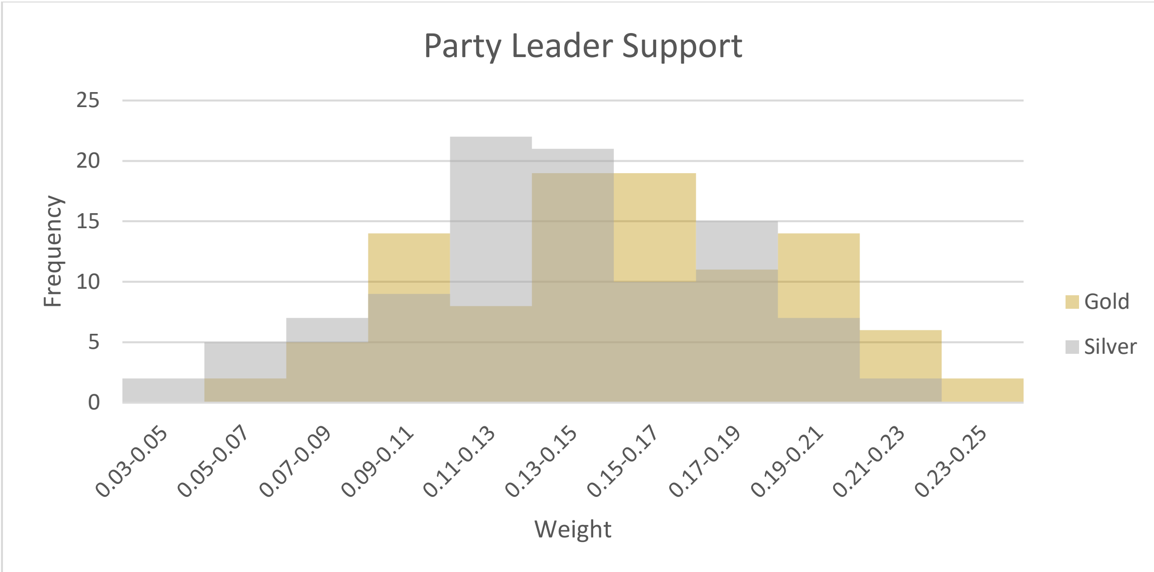
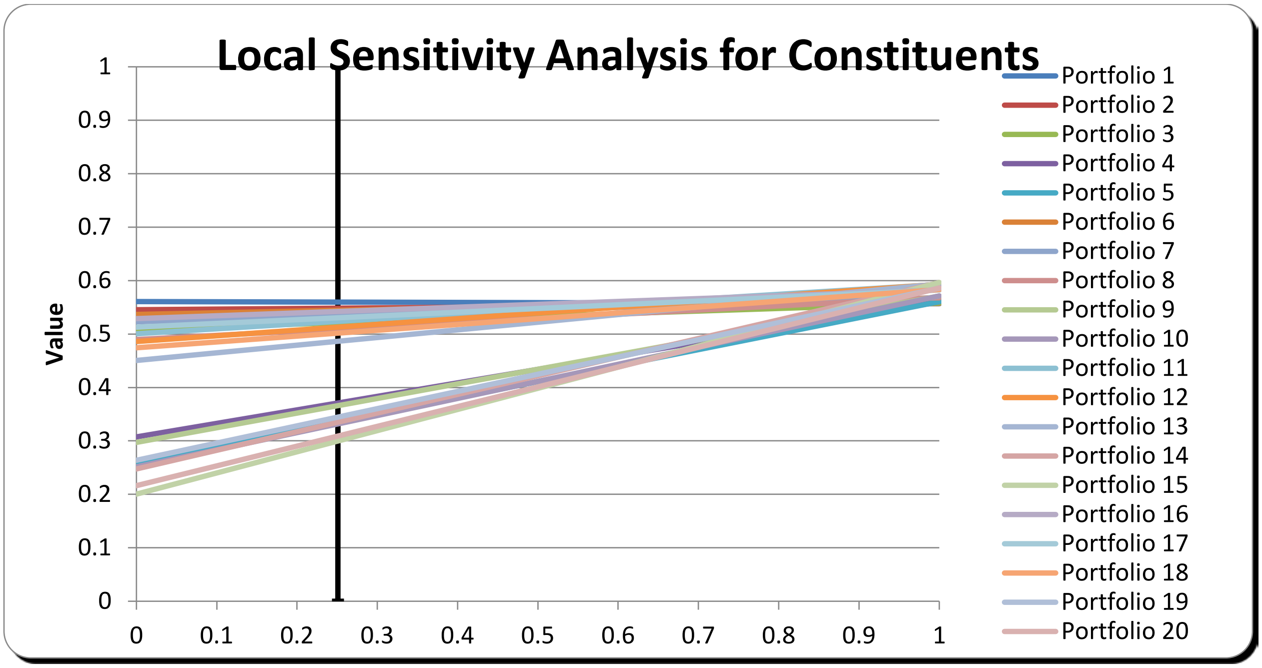


Figure 59: Party Leader Support Weight Distribution by Political Party

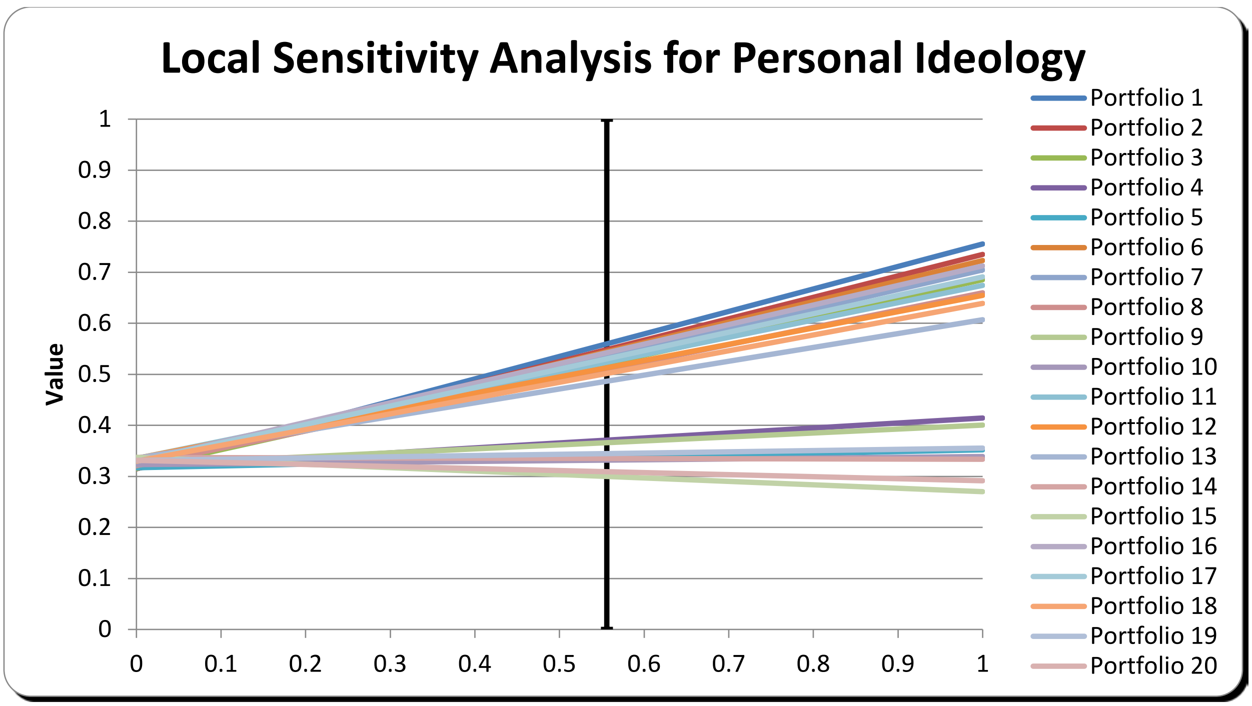
Appendix III: Sensitivity Analyses

Sensitivity Diagrams

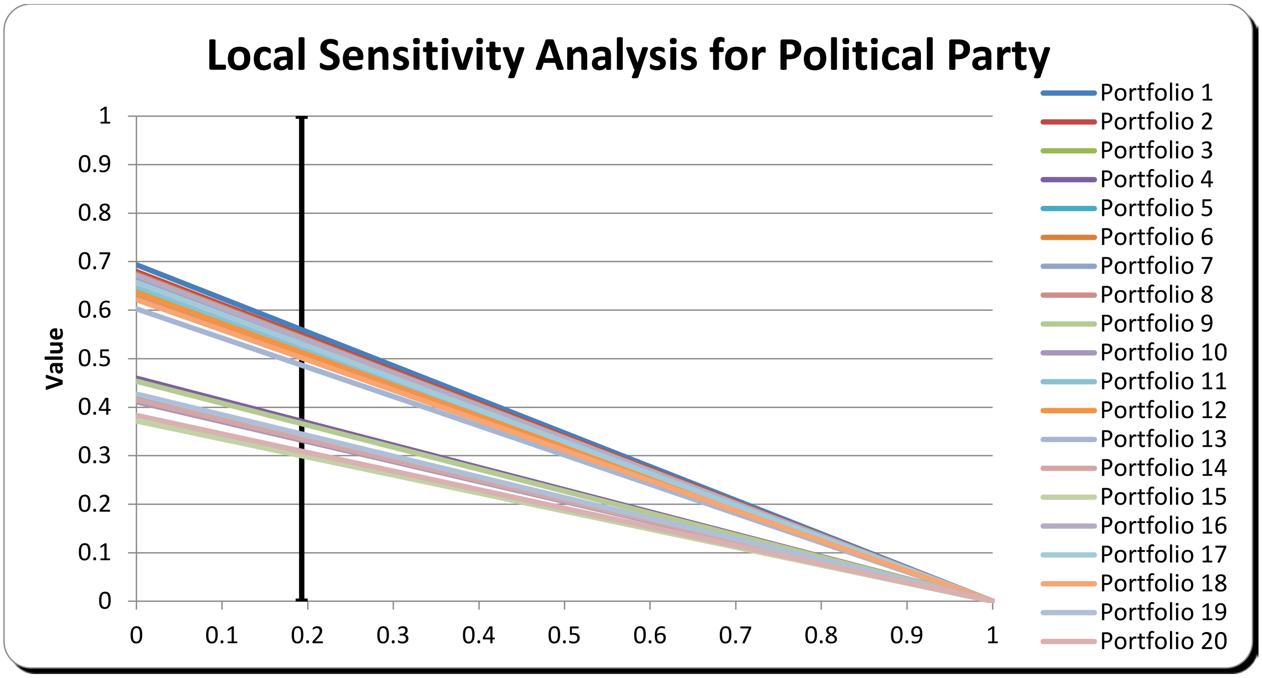
1. Silver Party Leader
   a. Local Sensitivity Graphs
      i. Constituent Satisfaction



      ii. Personal Ideology

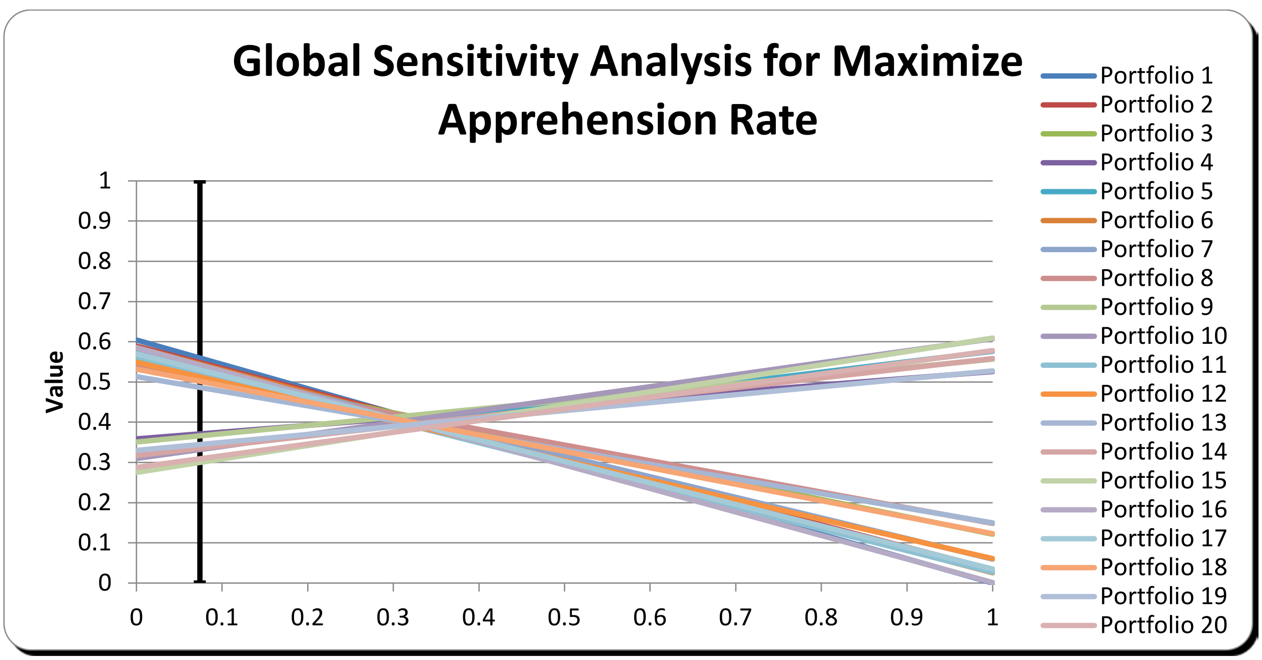


iii. Party Leader Support

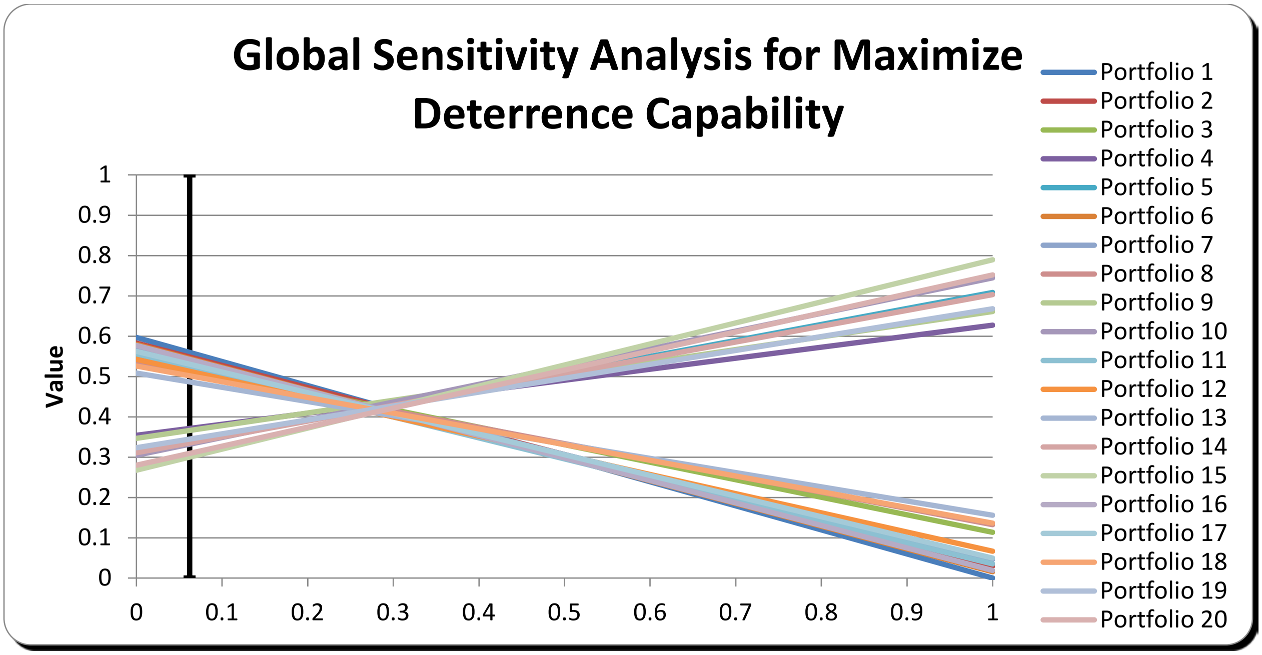


b. Global Sensitivity Graphs

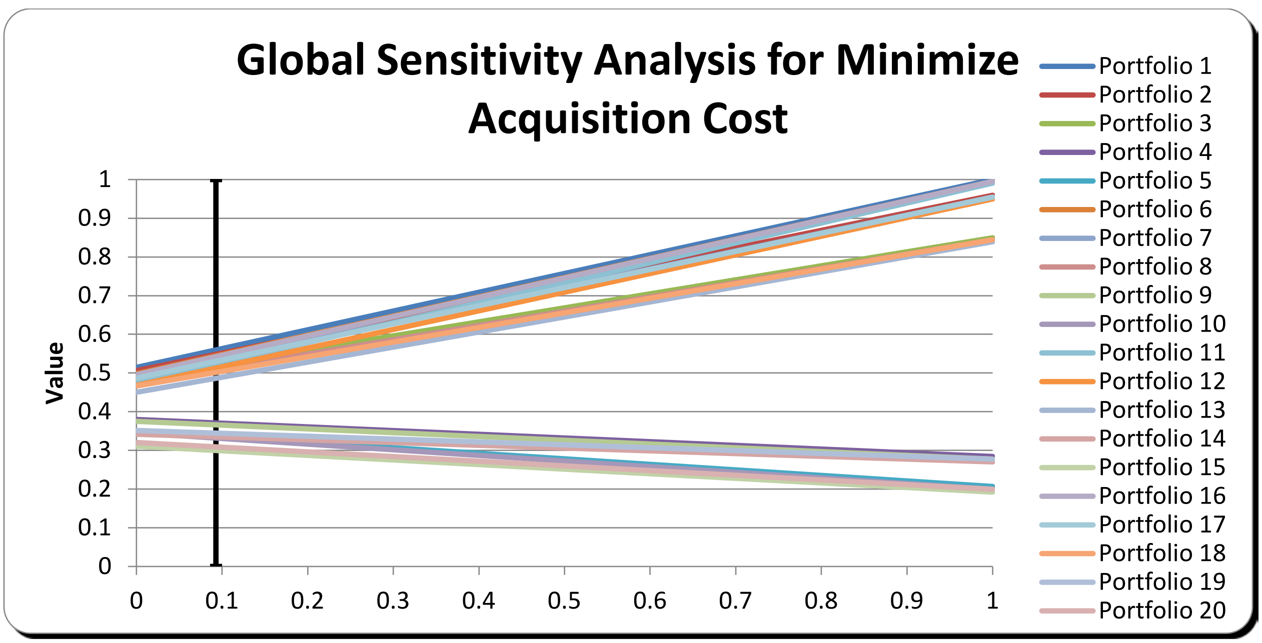
i. Maximize Apprehension Capability



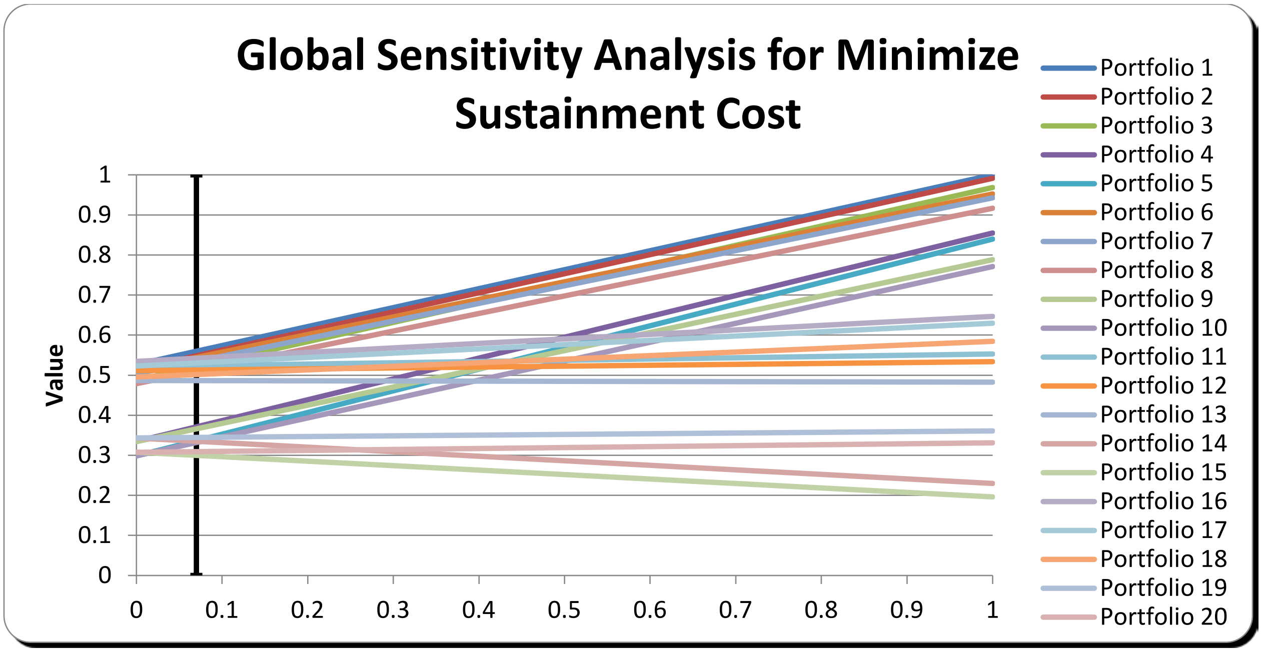
ii. Maximize Deterrence Value



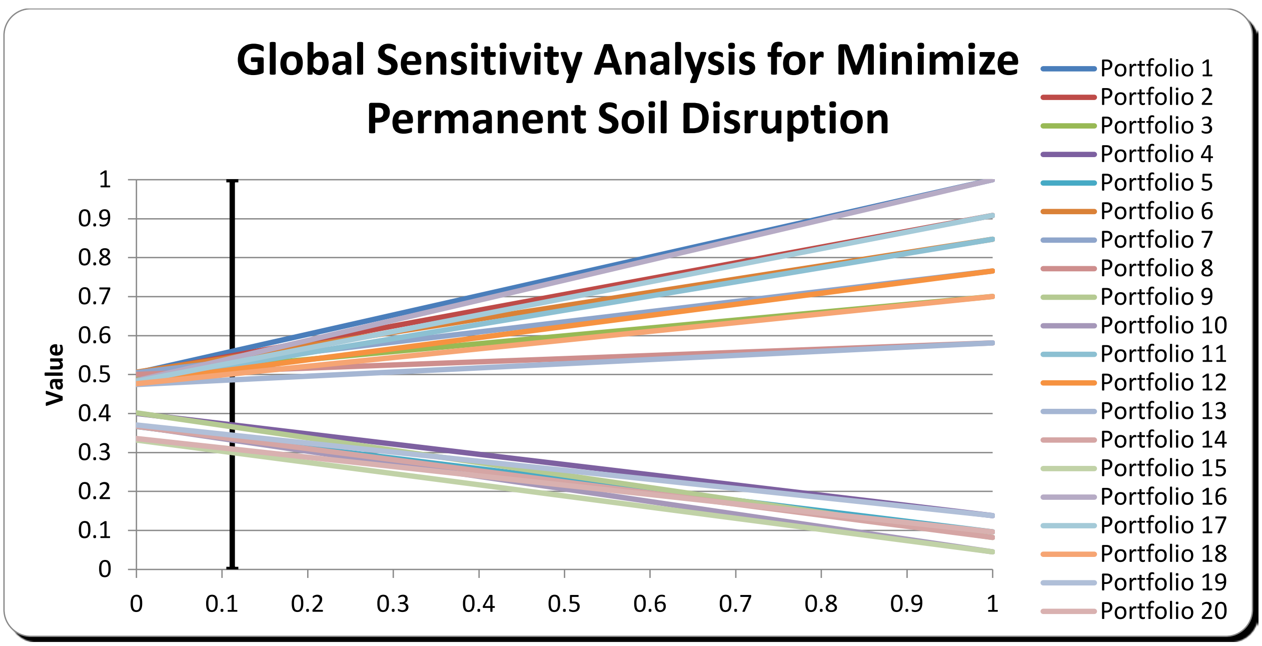
i. Minimize Acquisition Cost



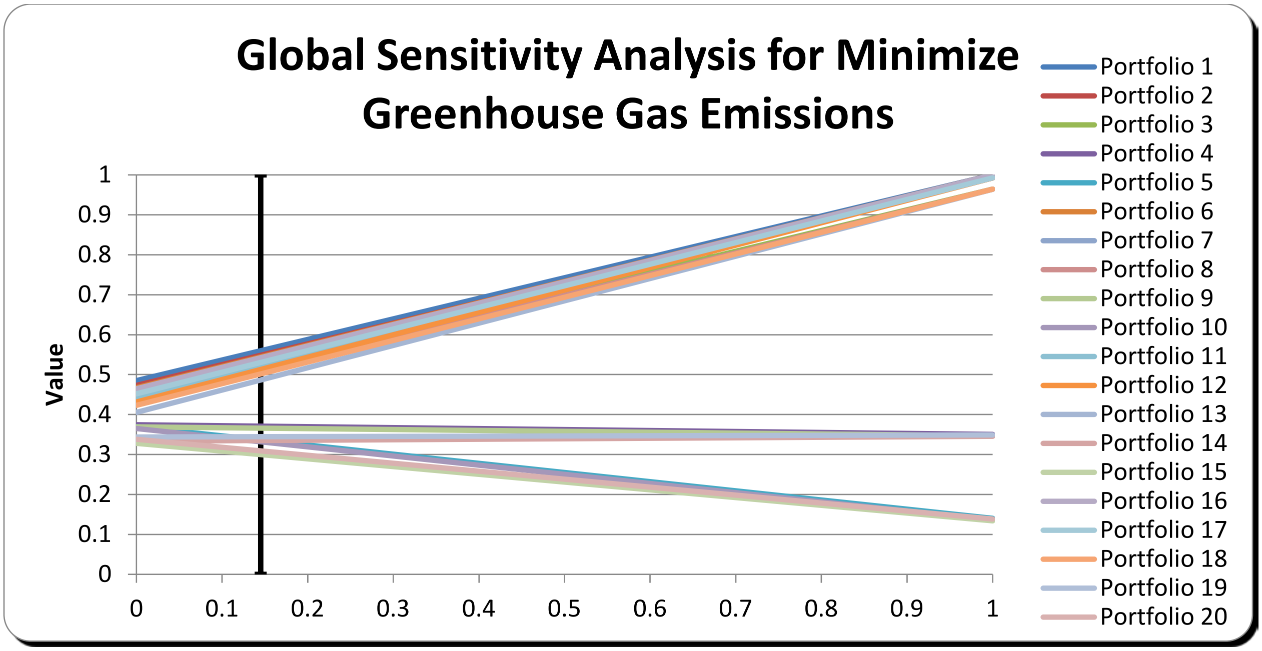
ii. Minimize Sustainment Cost



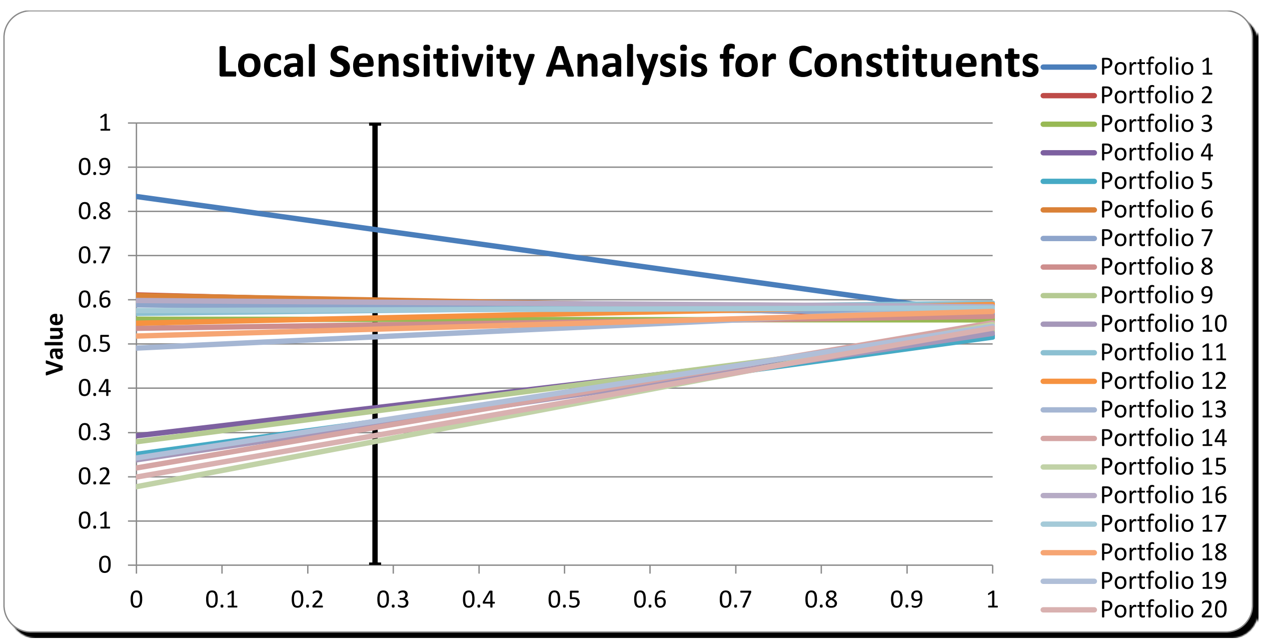
iii. Minimize Permanent Soil Disruption



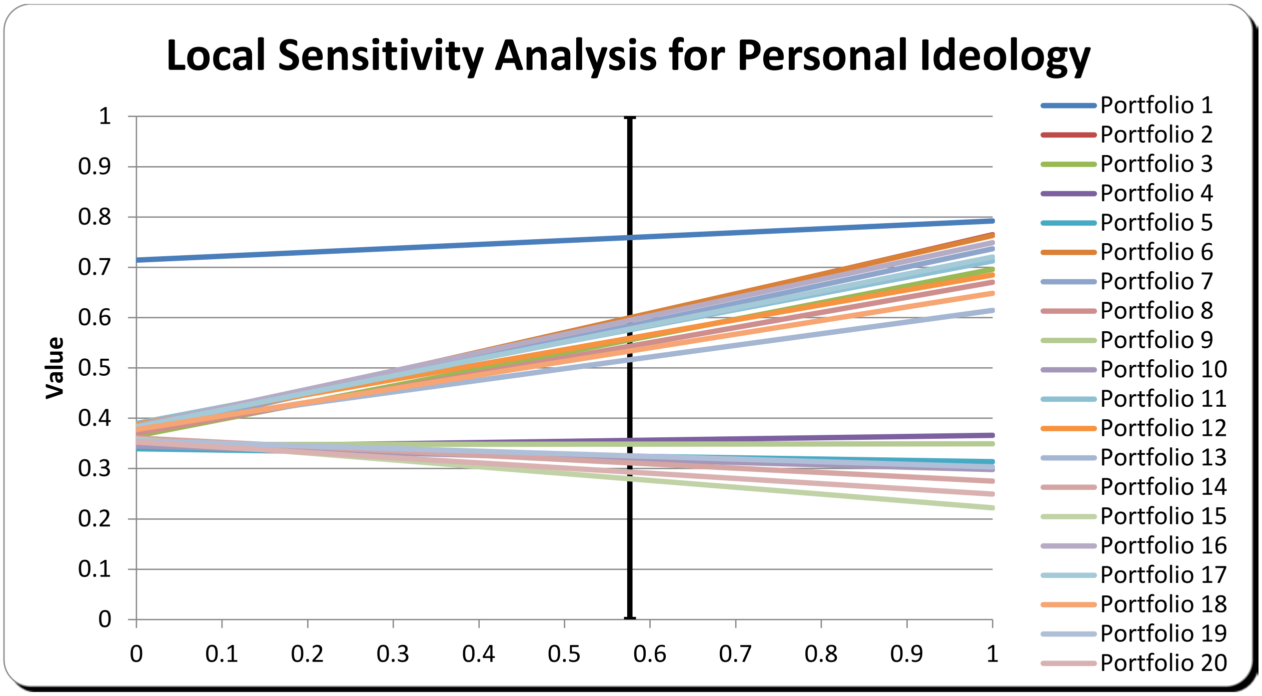
iv. Minimize Greenhouse Gas Emissions



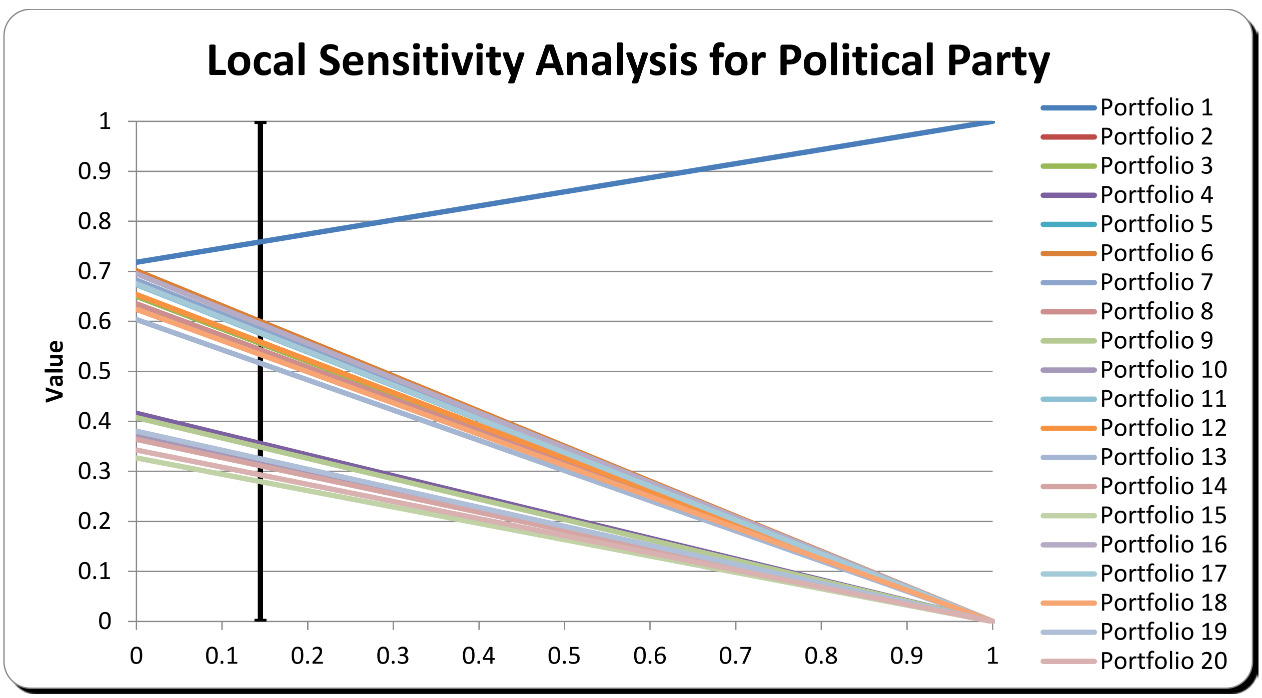
2. Silver Party DM # 2
   a. Local Sensitivity Graphs
      i. Constituent Satisfaction



ii. Personal Ideology

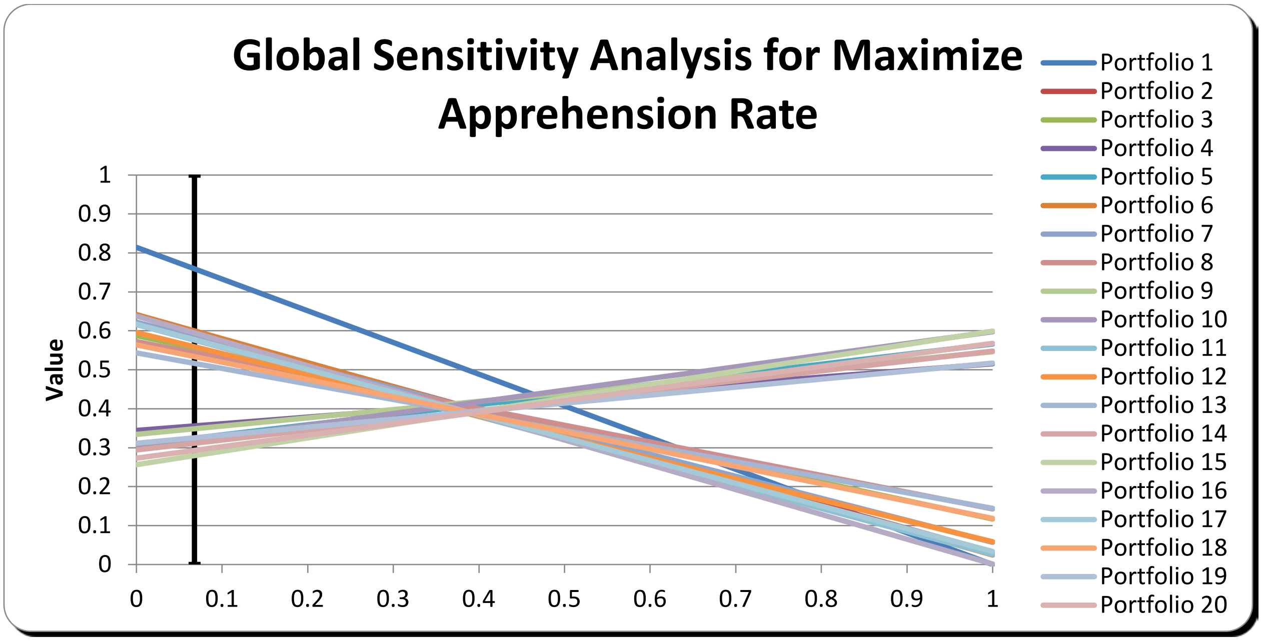


iii. Party Leader Support

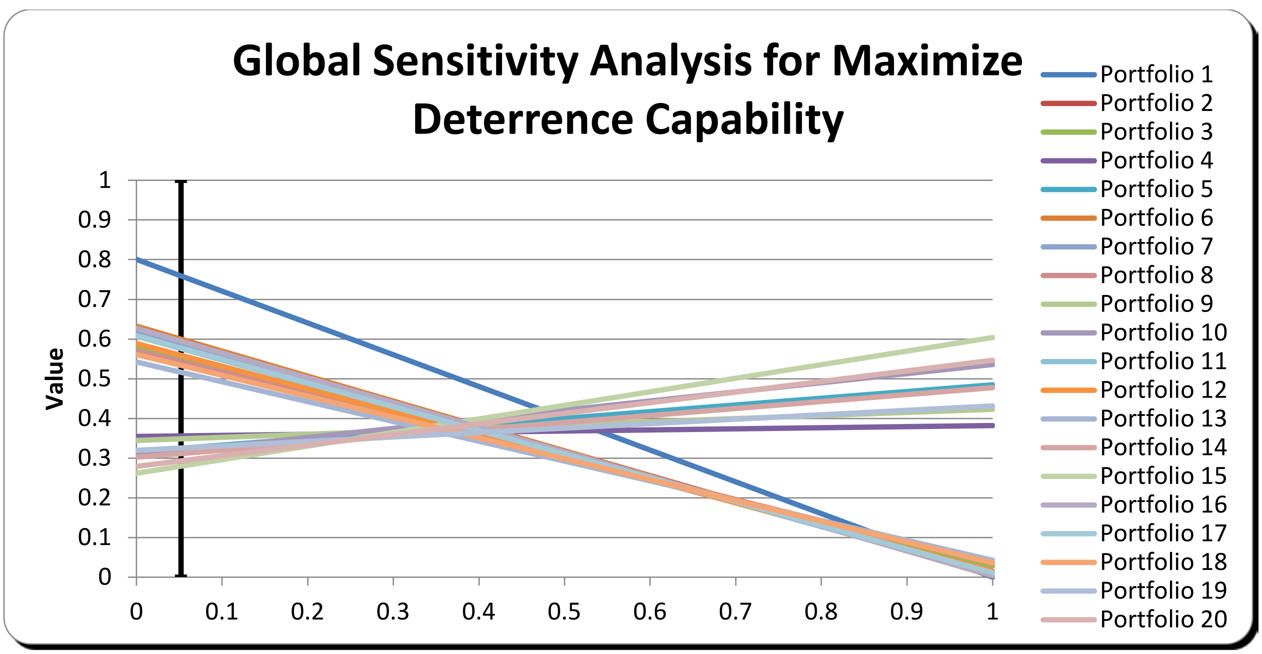


b. Global Sensitivity Graphs

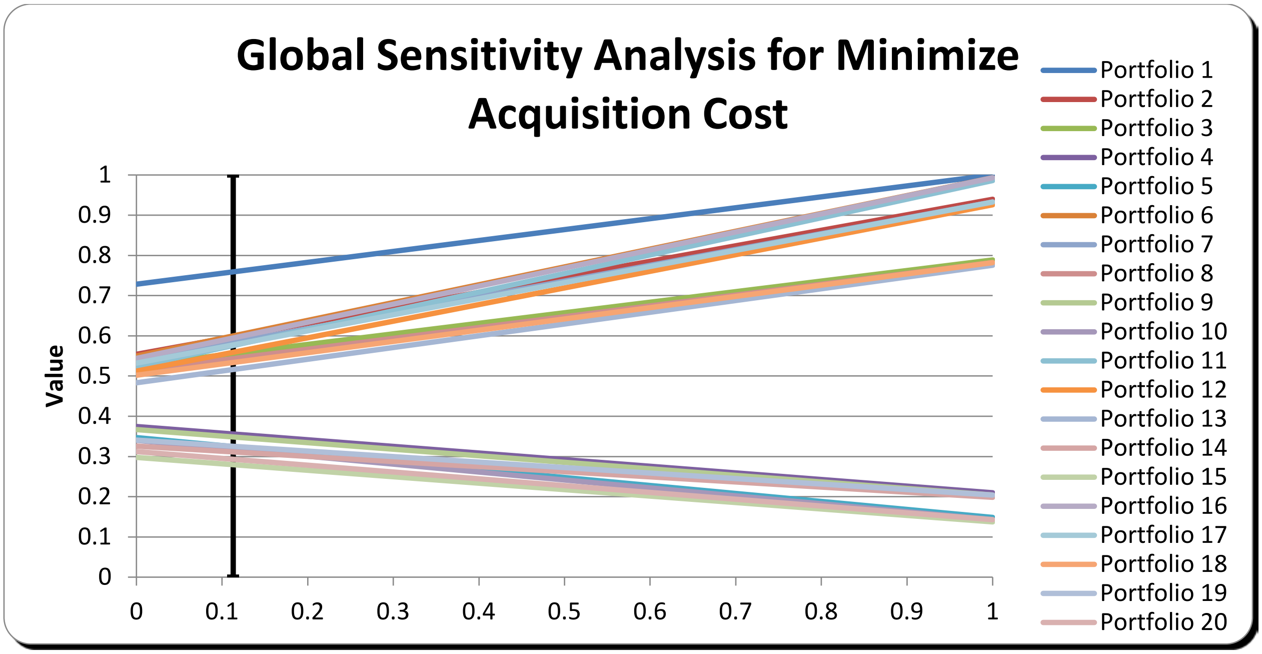
i. Maximize Apprehension Capability



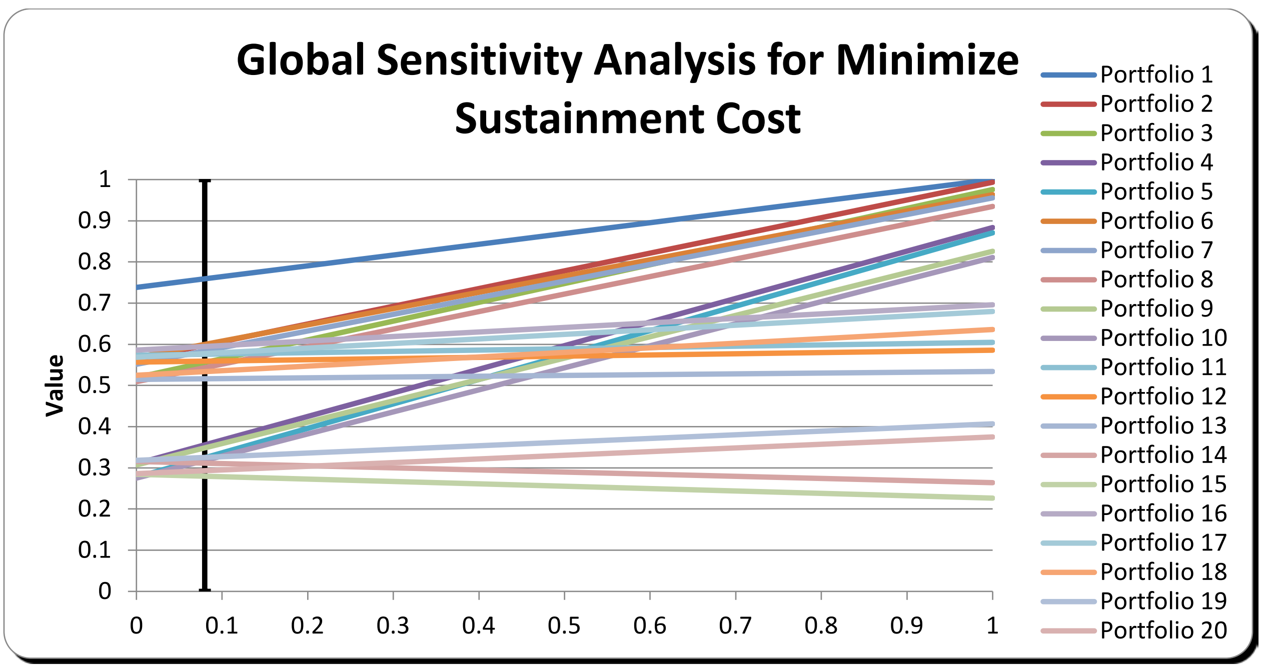
ii. Maximize Deterrence Capability



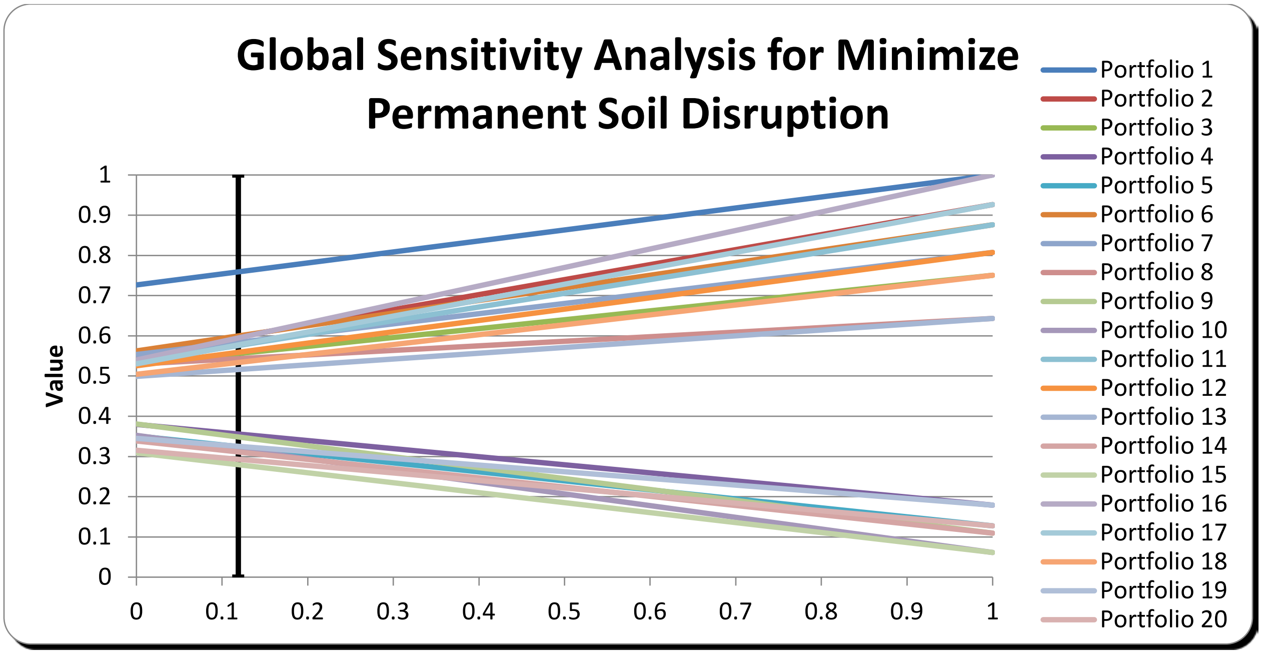
iii. Minimize Acquisition Cost



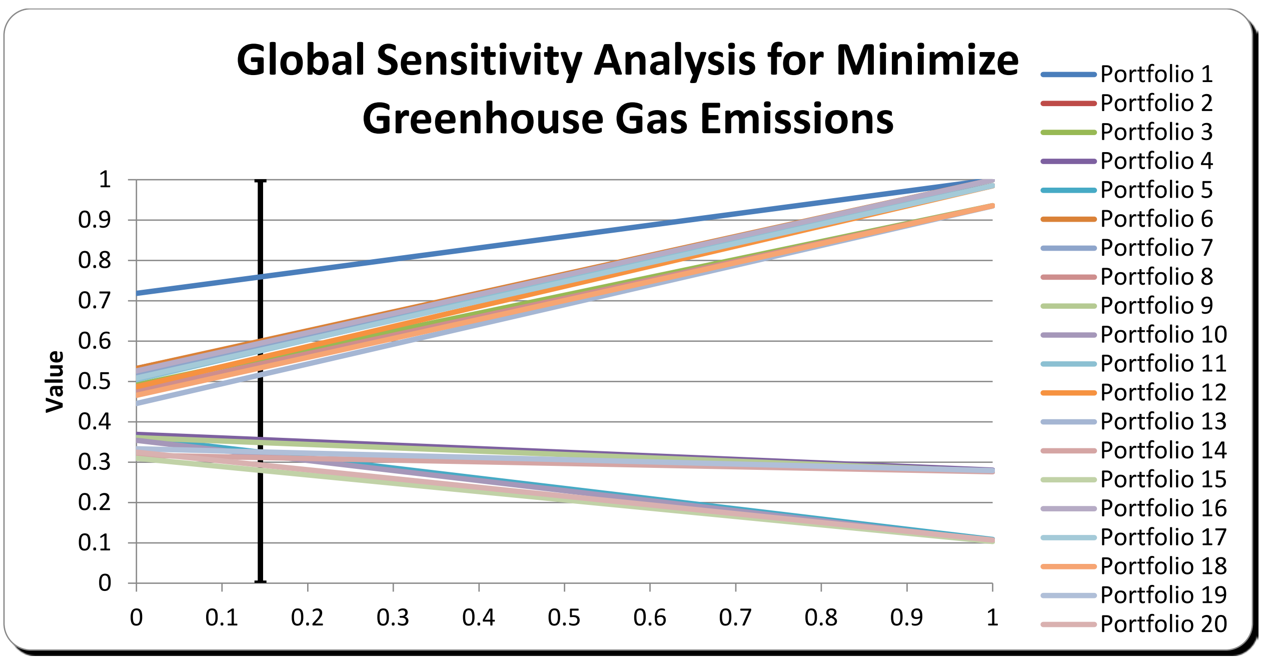
iv. Minimize Sustainment Cost



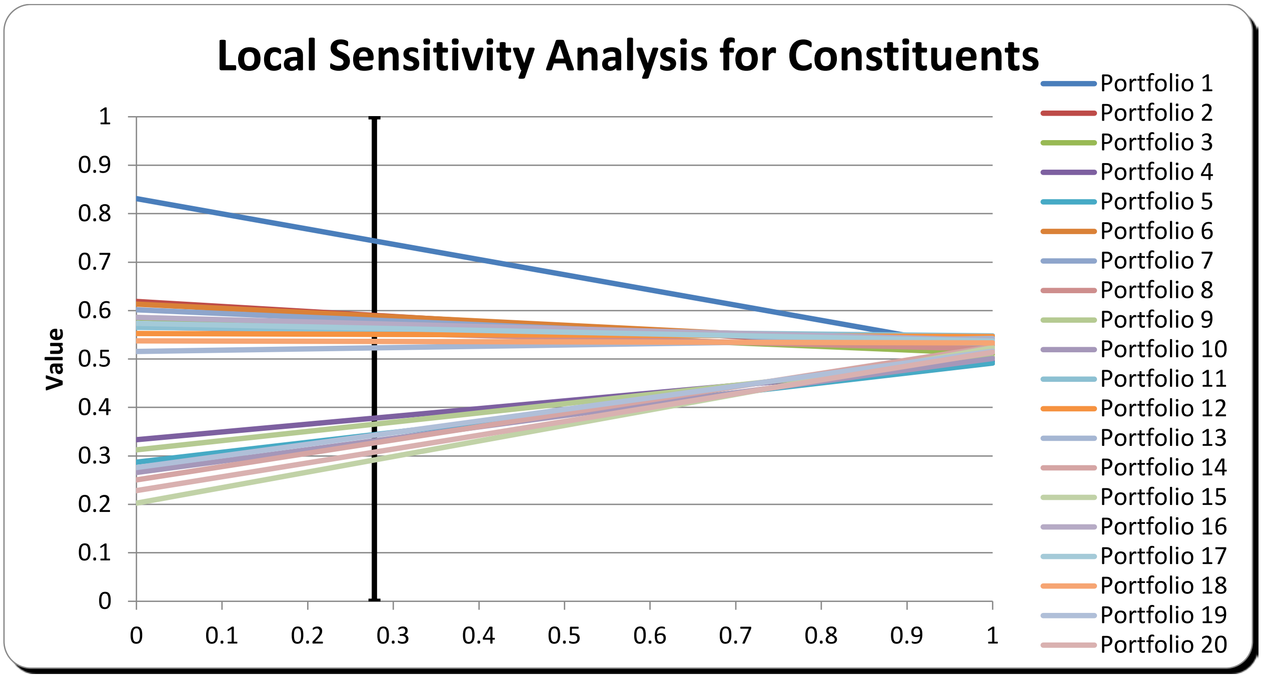
v. Minimize Permanent Soil Disruption



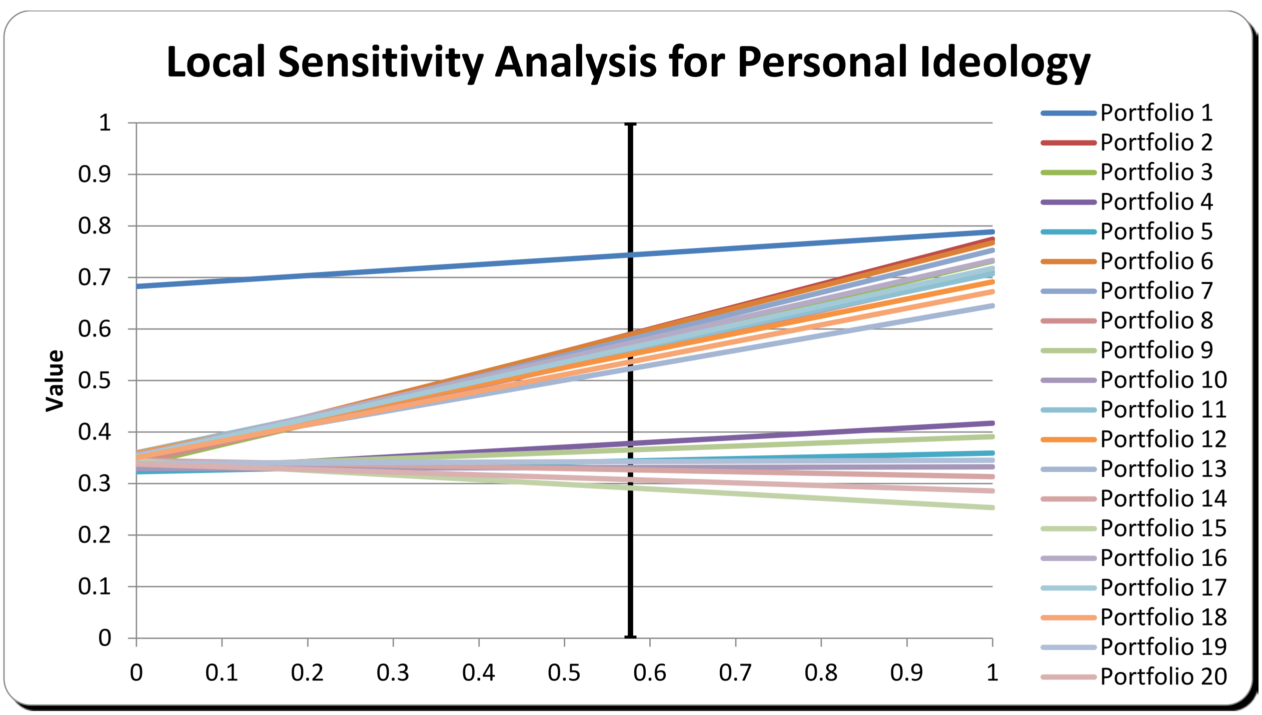
vi. Minimize Greenhouse Gas Emissions



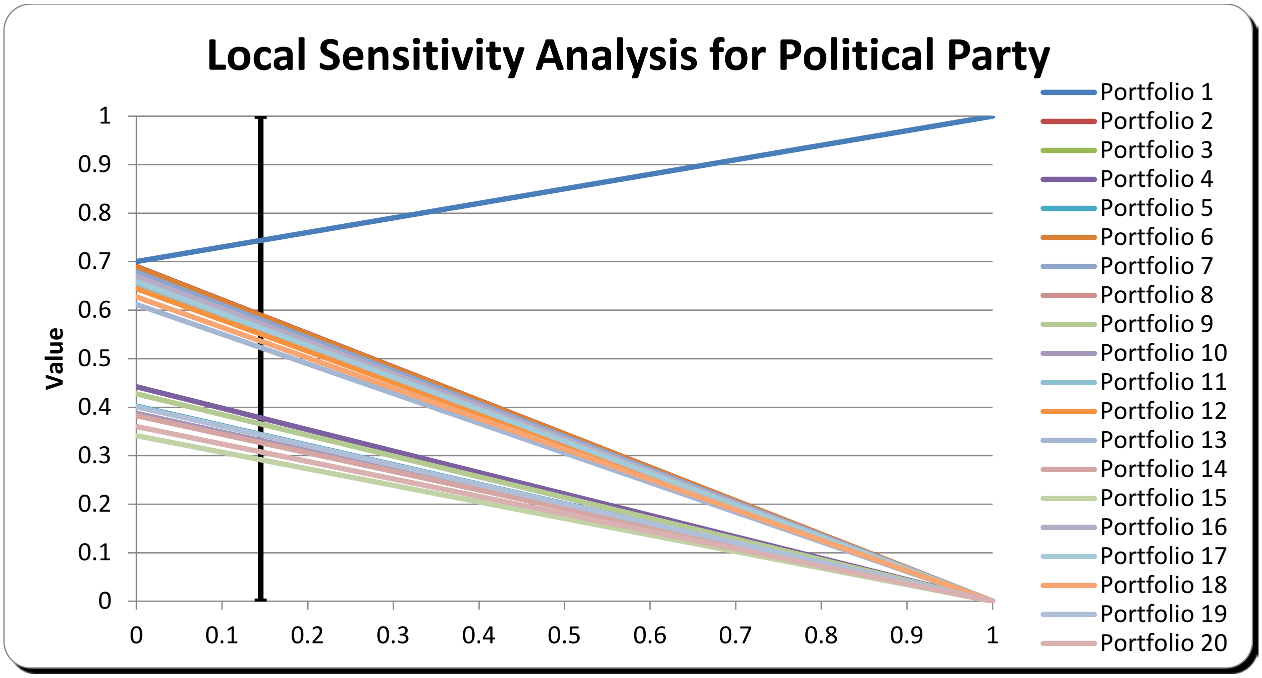
3. Silver Party DM # 3
    a. Local Sensitivity Graphs
        i. Constituent Satisfaction



        ii. Personal Ideology

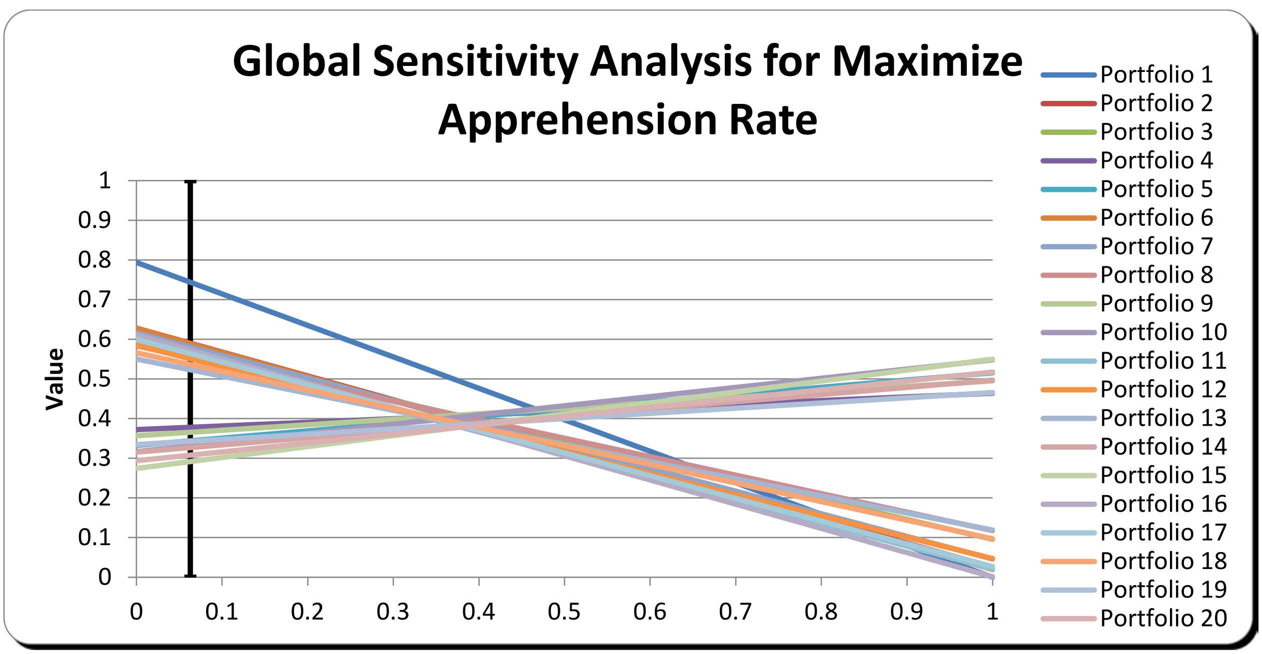


iii. Party Leader Support

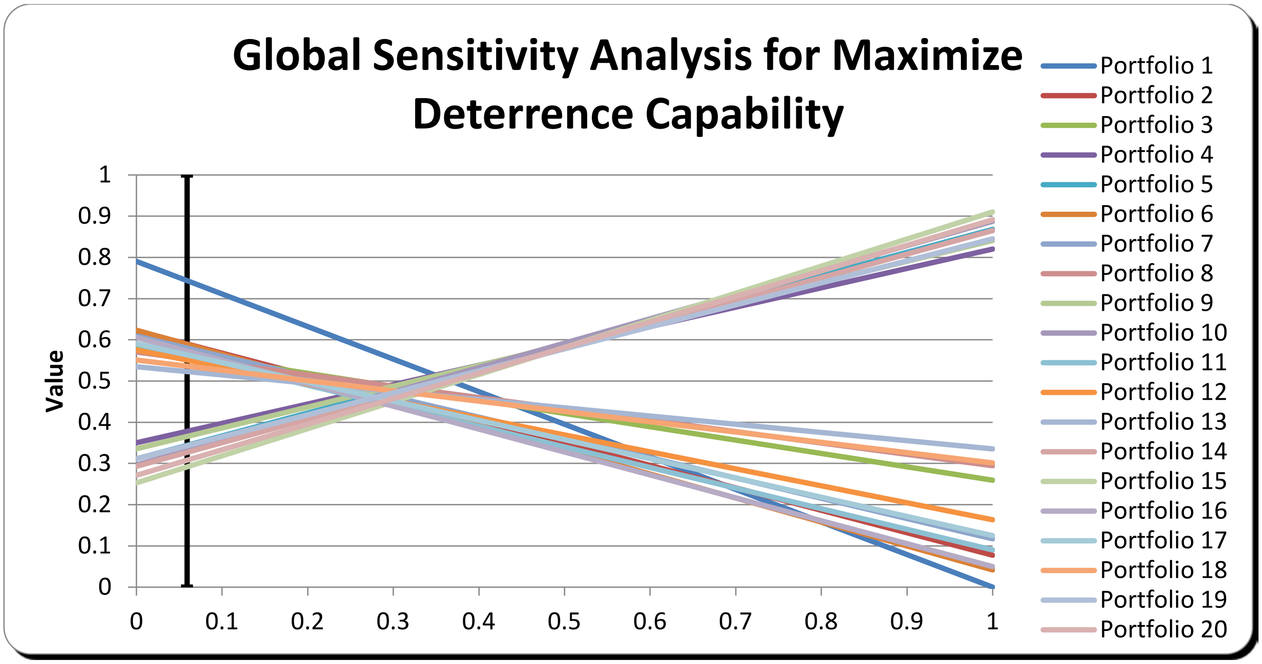


b. Global Sensitivity Graphs

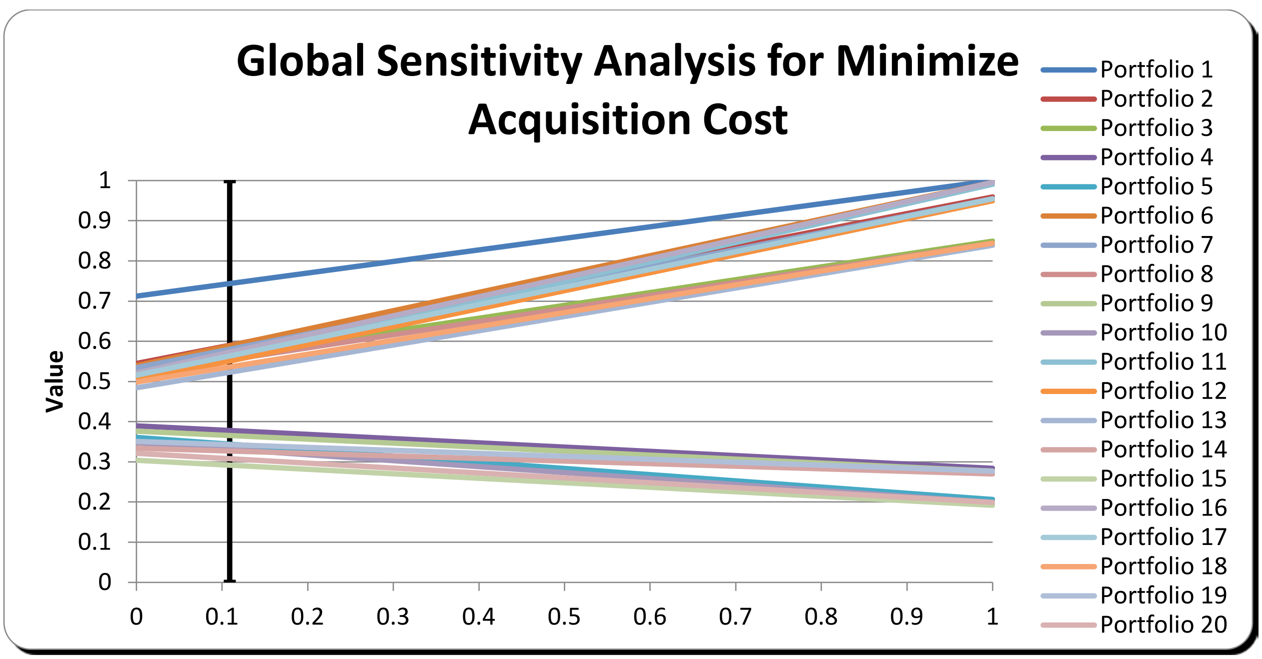
i. Maximize Apprehension Capability



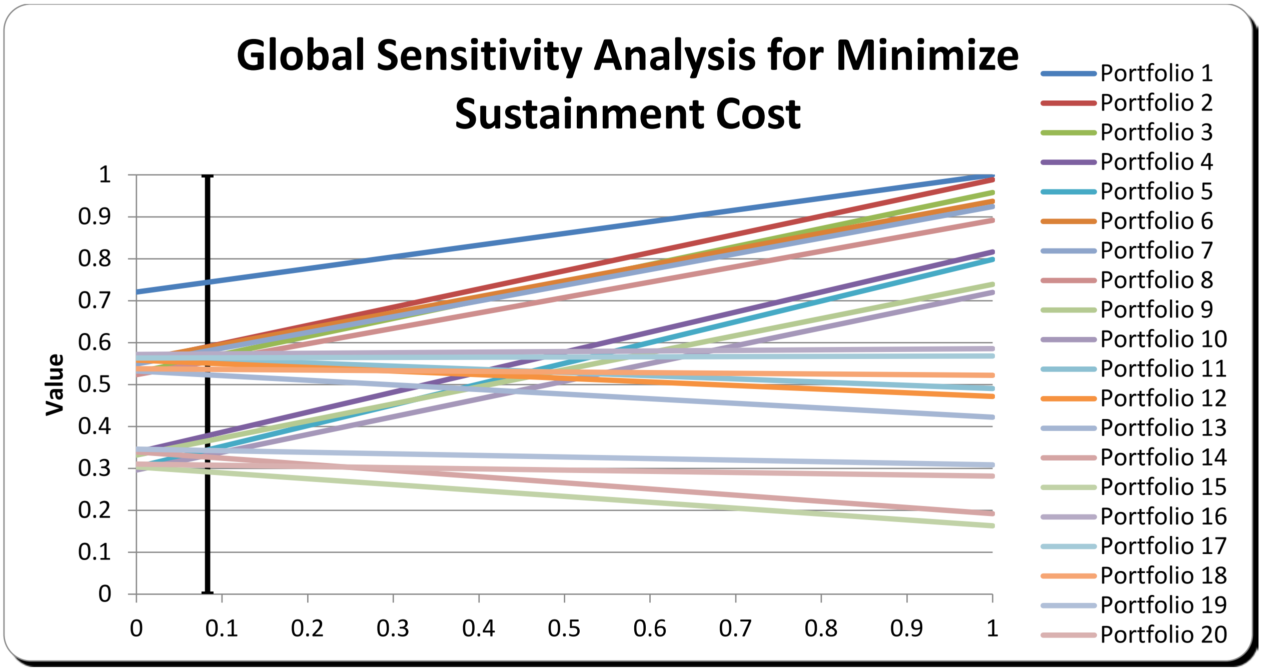
ii. Maximize Deterrence Capability



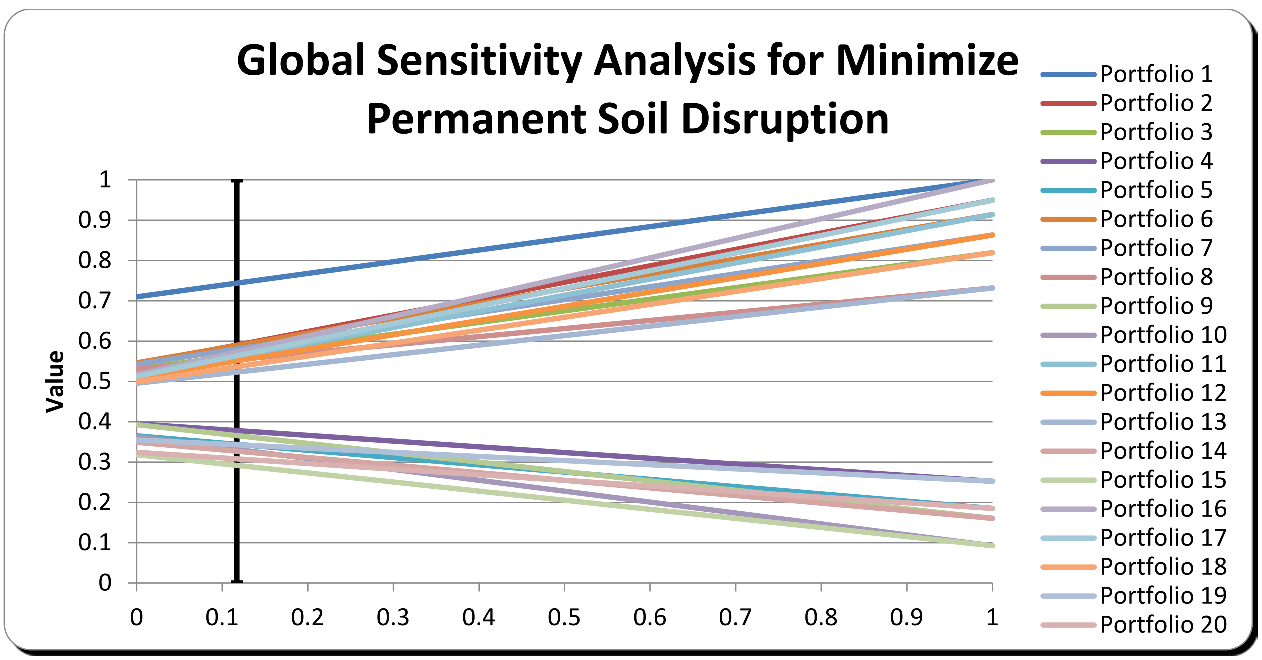
iii. Minimize Acquisition Cost



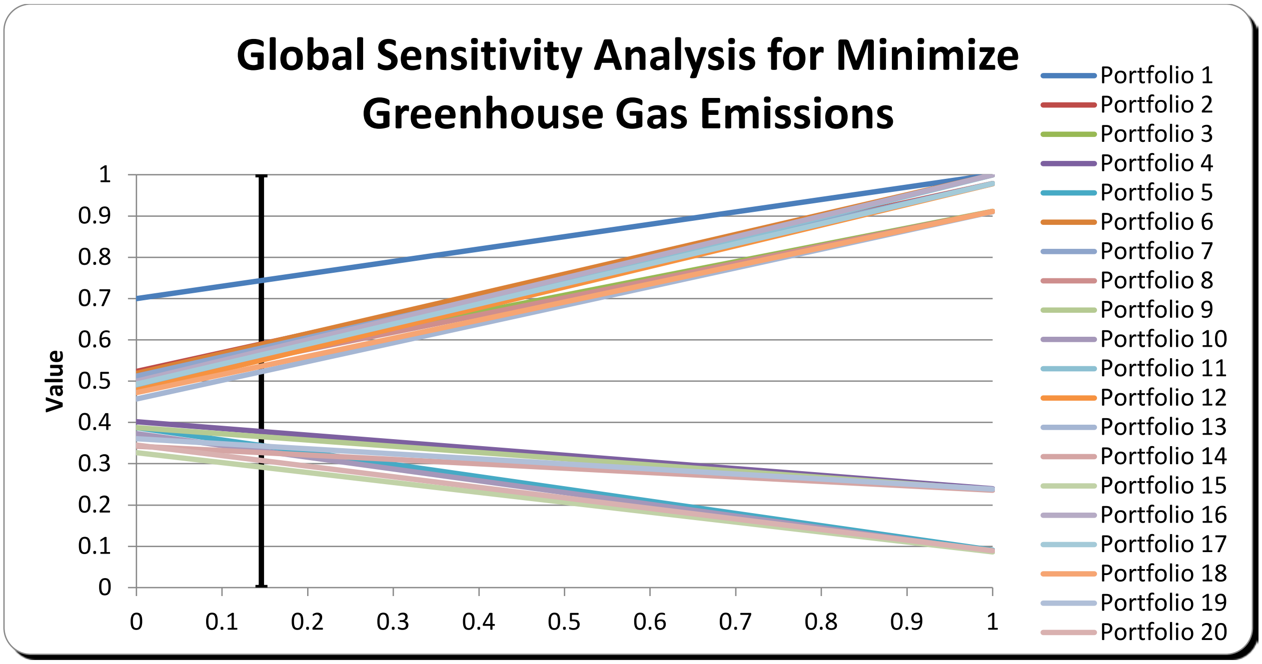
iv. Minimize Sustainment Cost



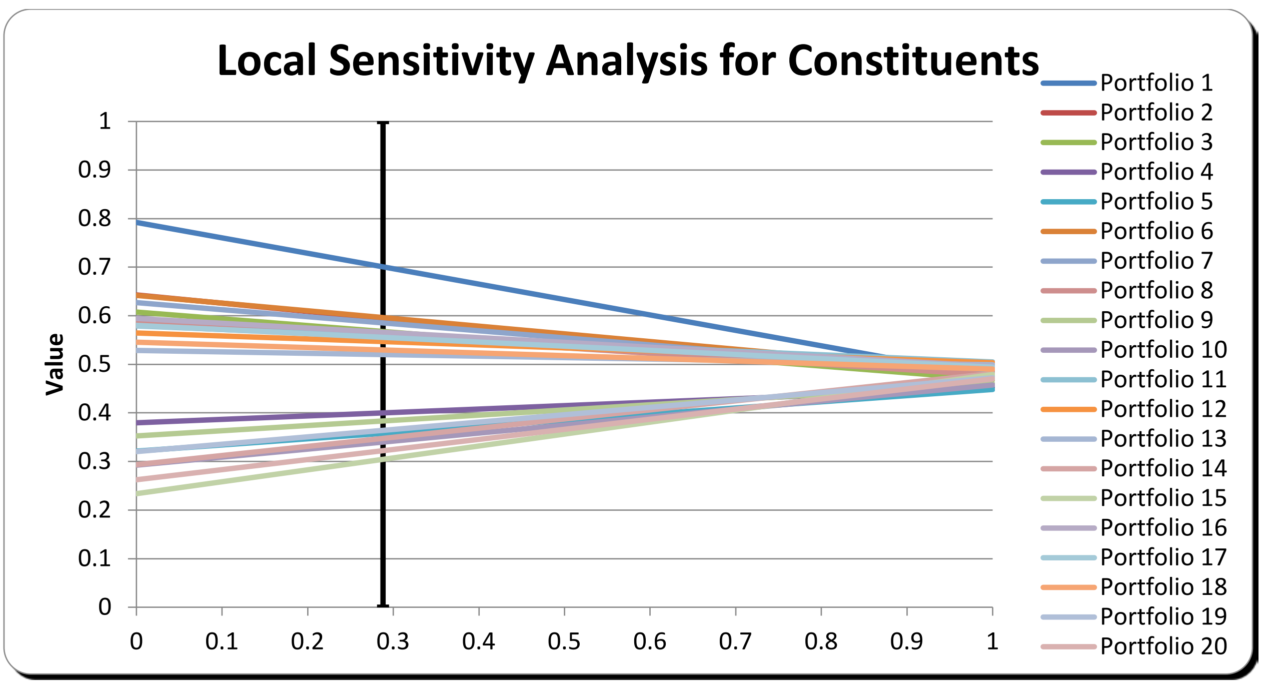
v. Minimize Permanent Soil Disruption



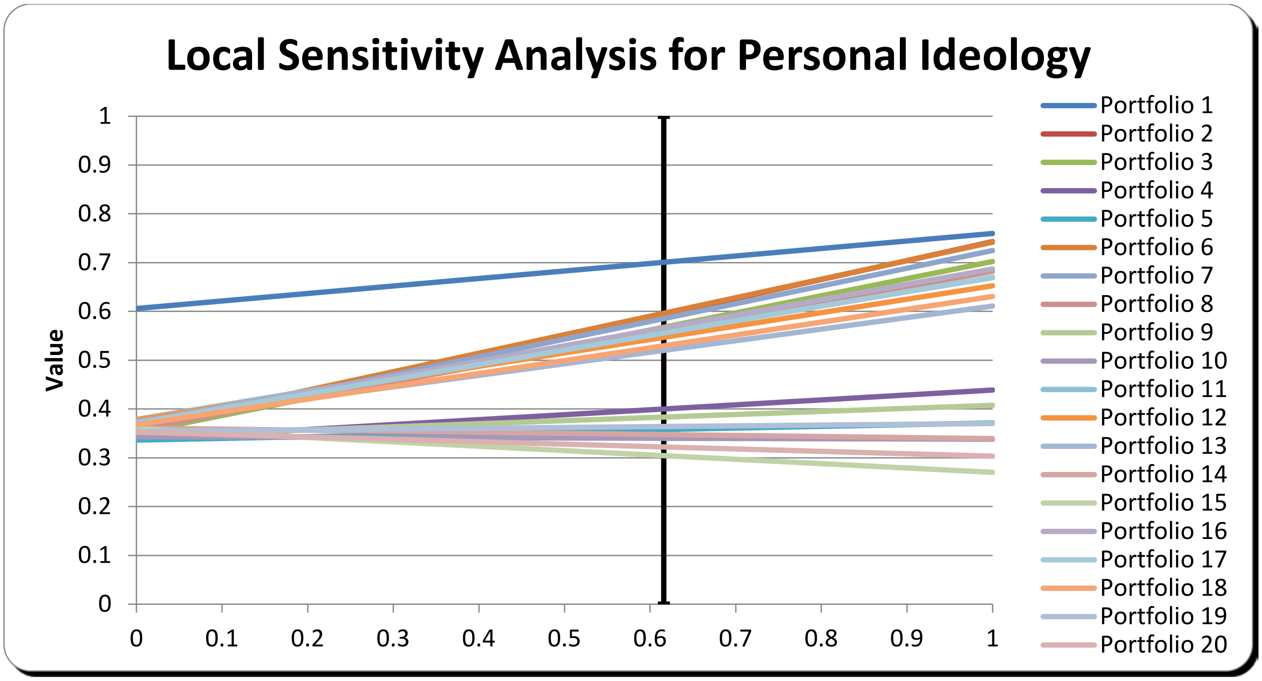
vi. Minimize Greenhouse Gas Emissions



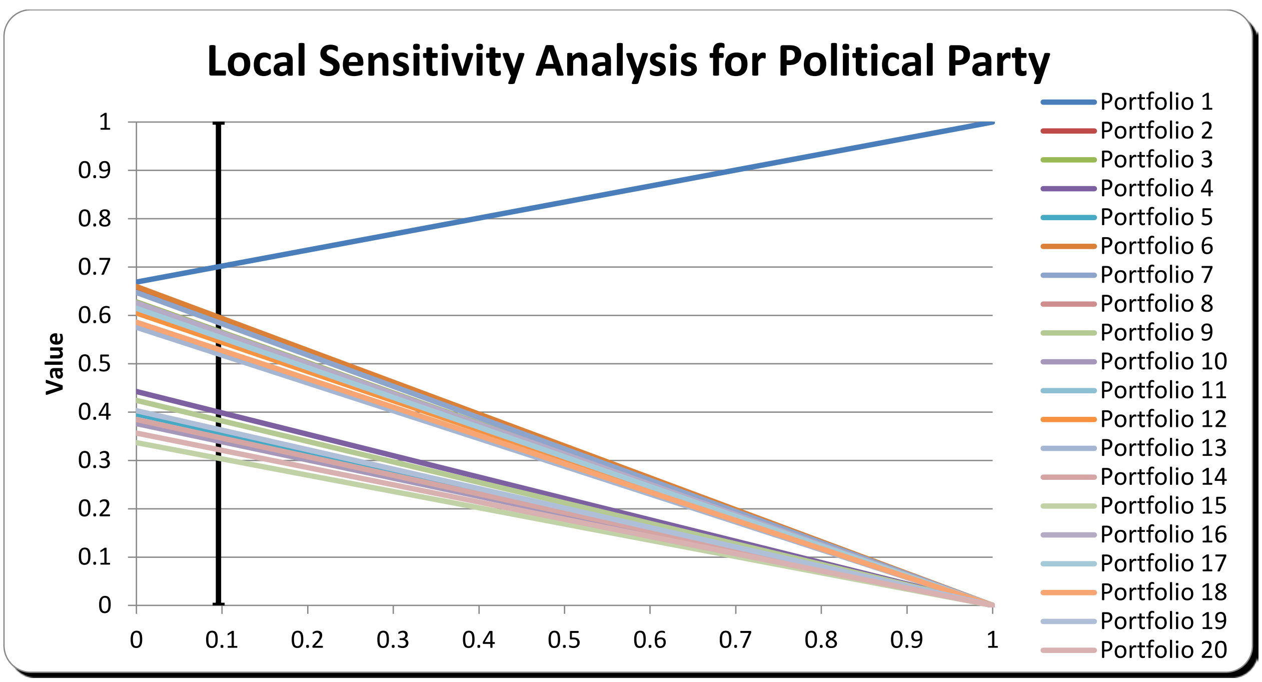
4. Silver Party DM # 4
   a. Local Sensitivity Graphs
      i. Constituent Satisfaction



ii. Personal Ideology

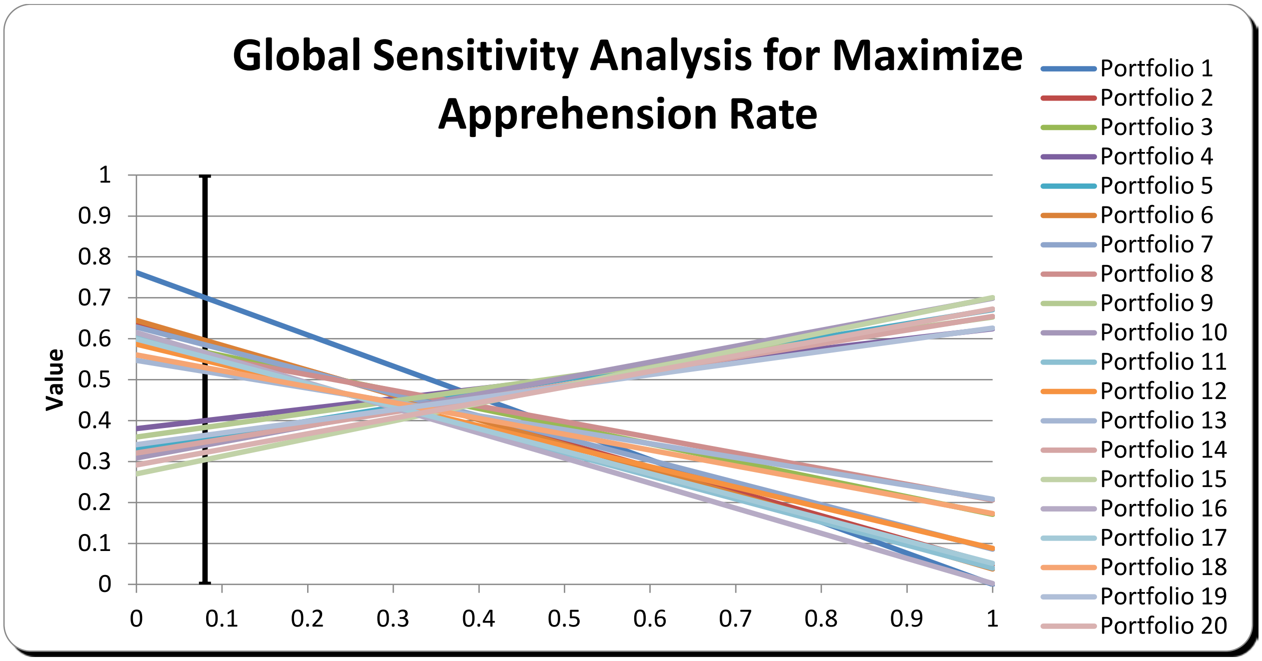


iii. Party Leader Support

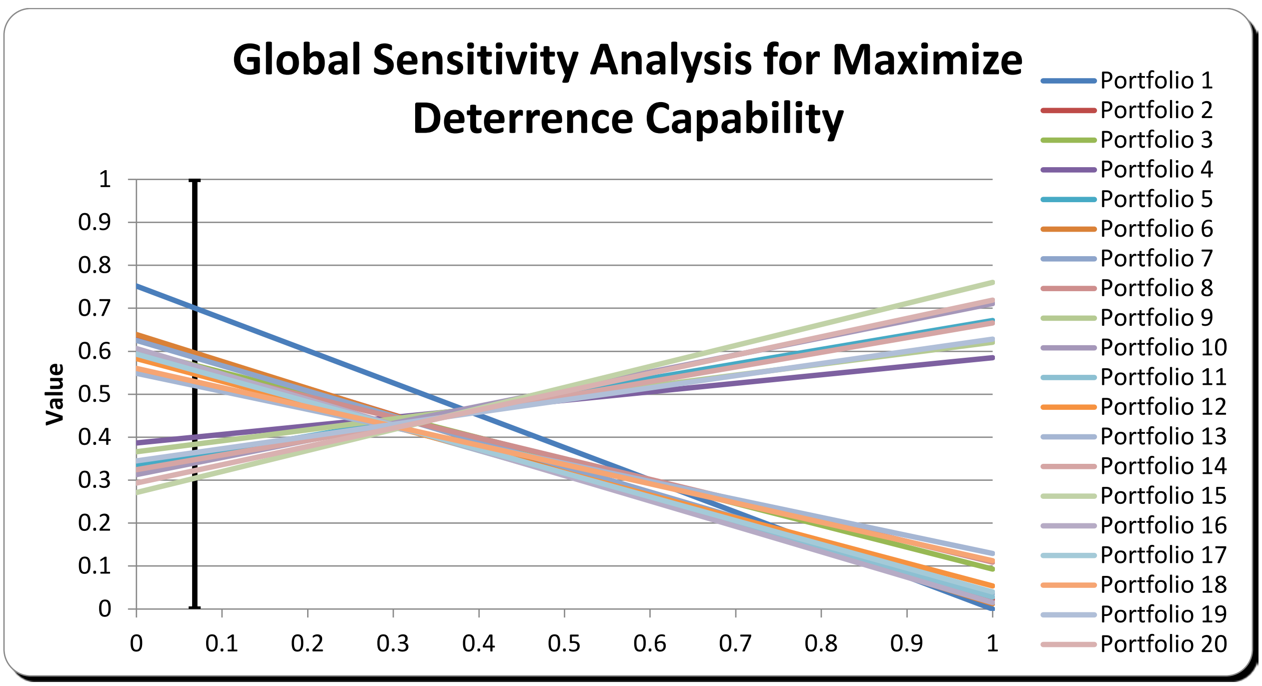


b. Global Sensitivity Graphs

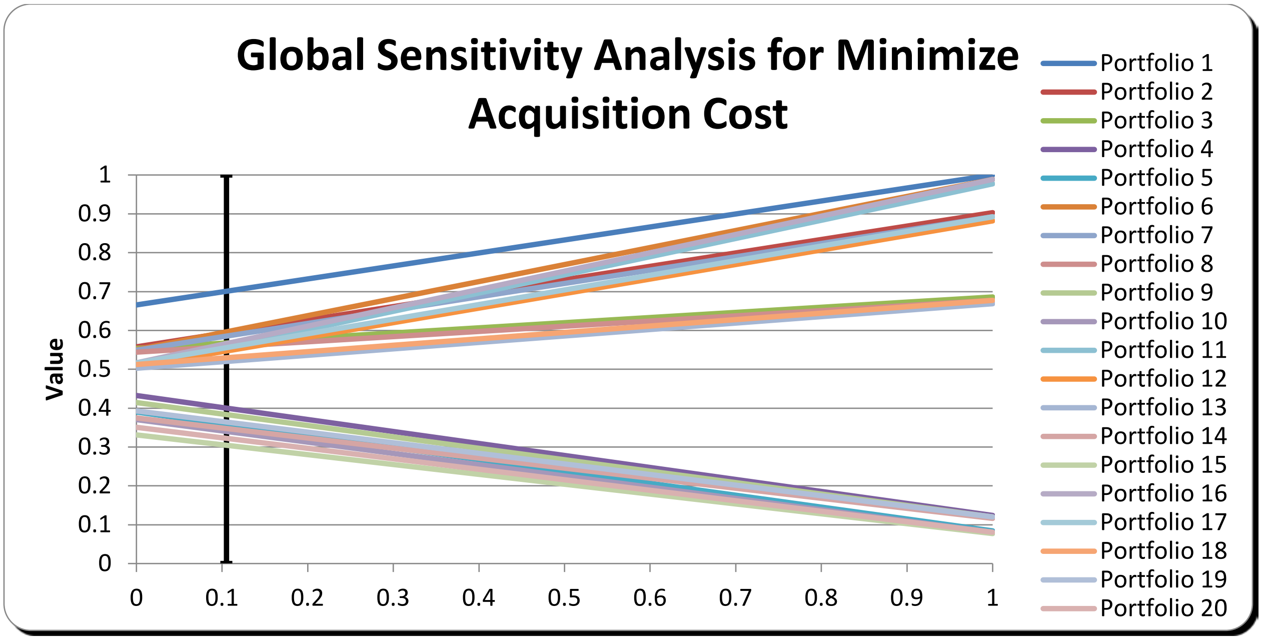
i. Maximize Apprehension Capability



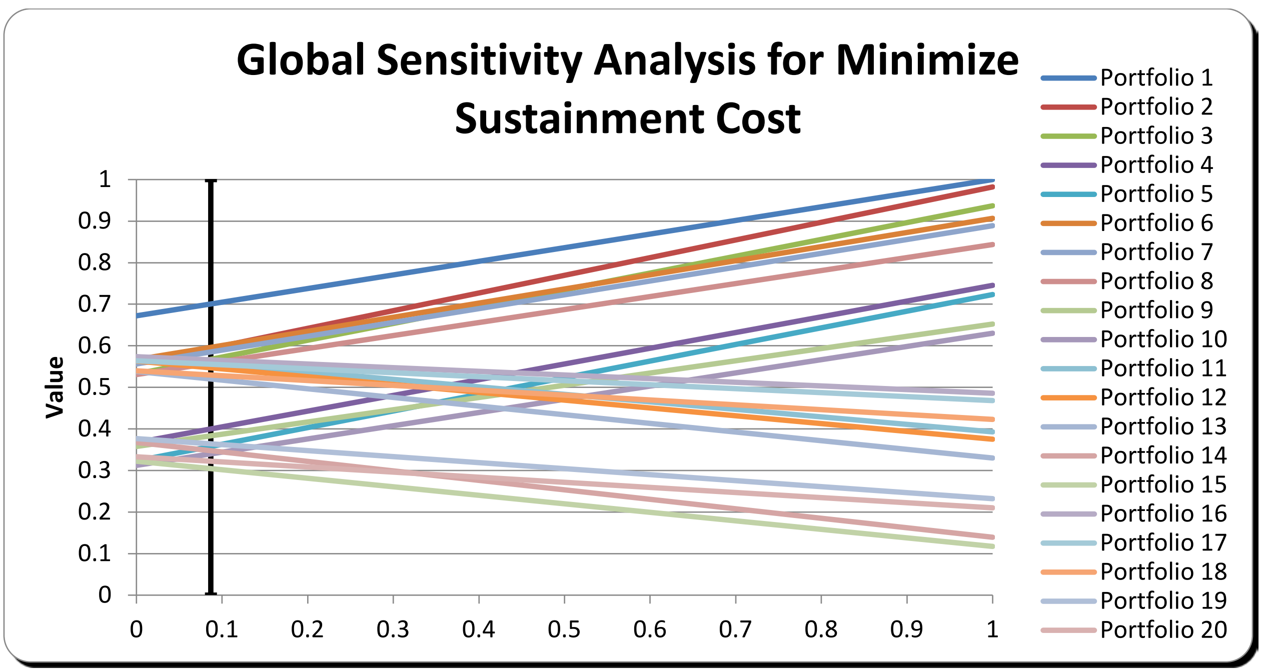
ii. Maximize Deterrence Capability



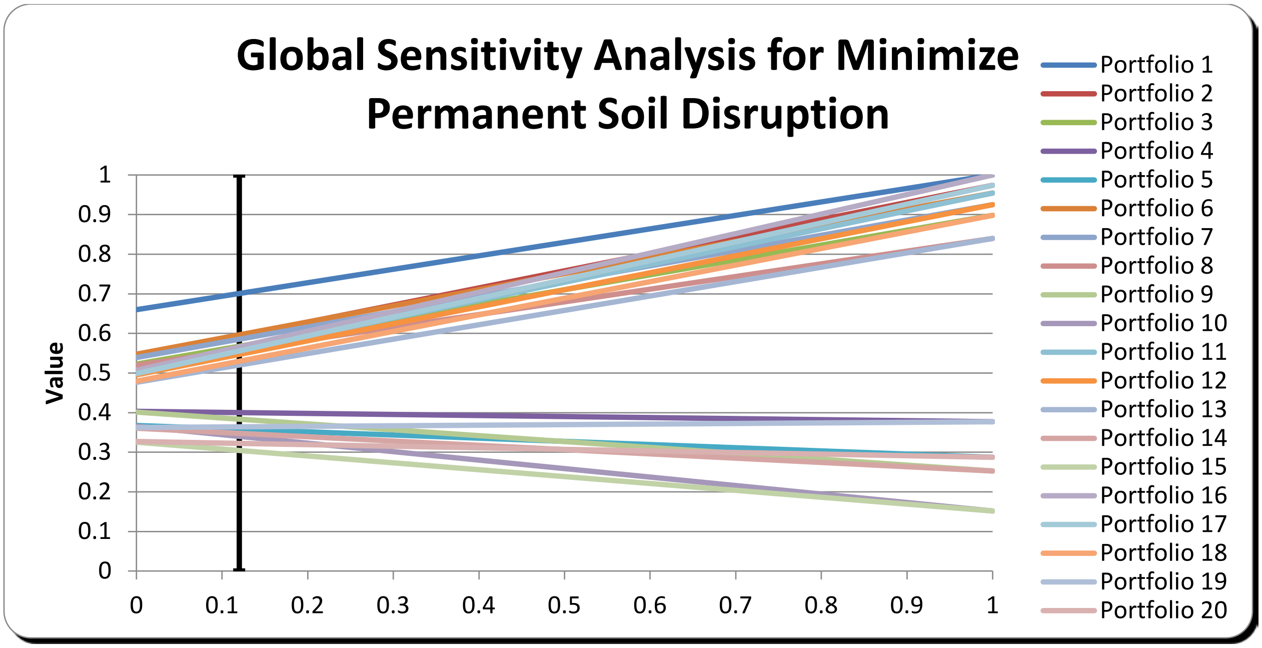
iii. Minimize Acquisition Cost



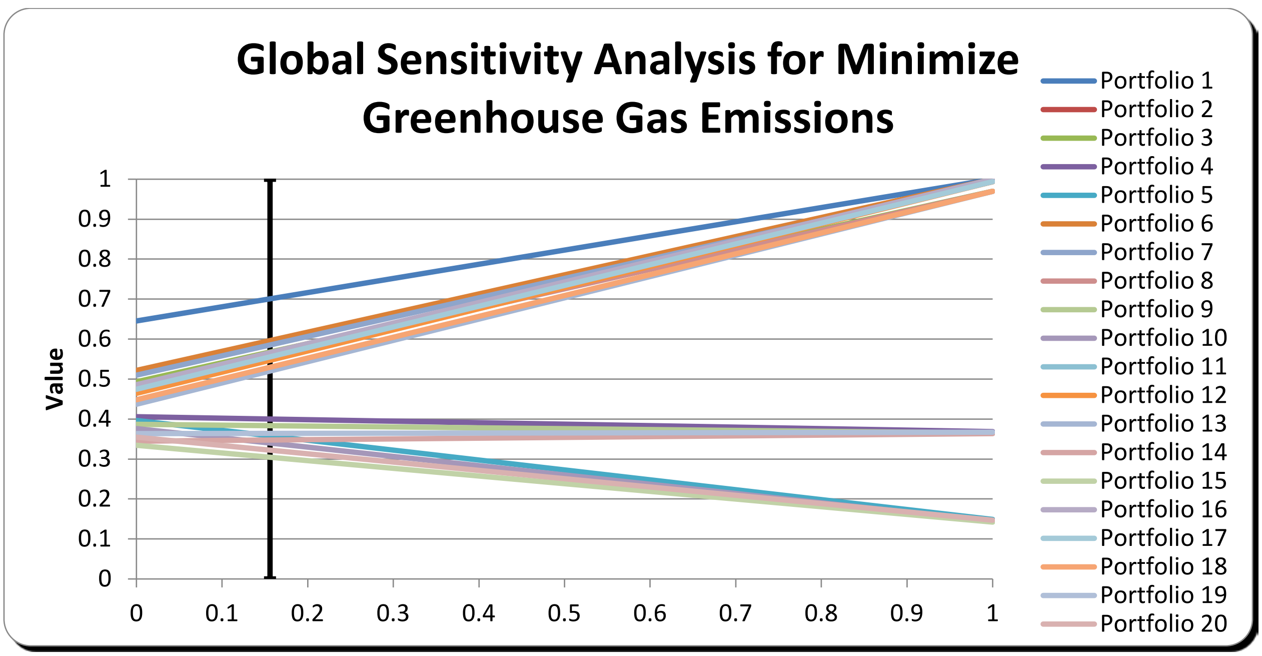
iv. Minimize Sustainment Cost



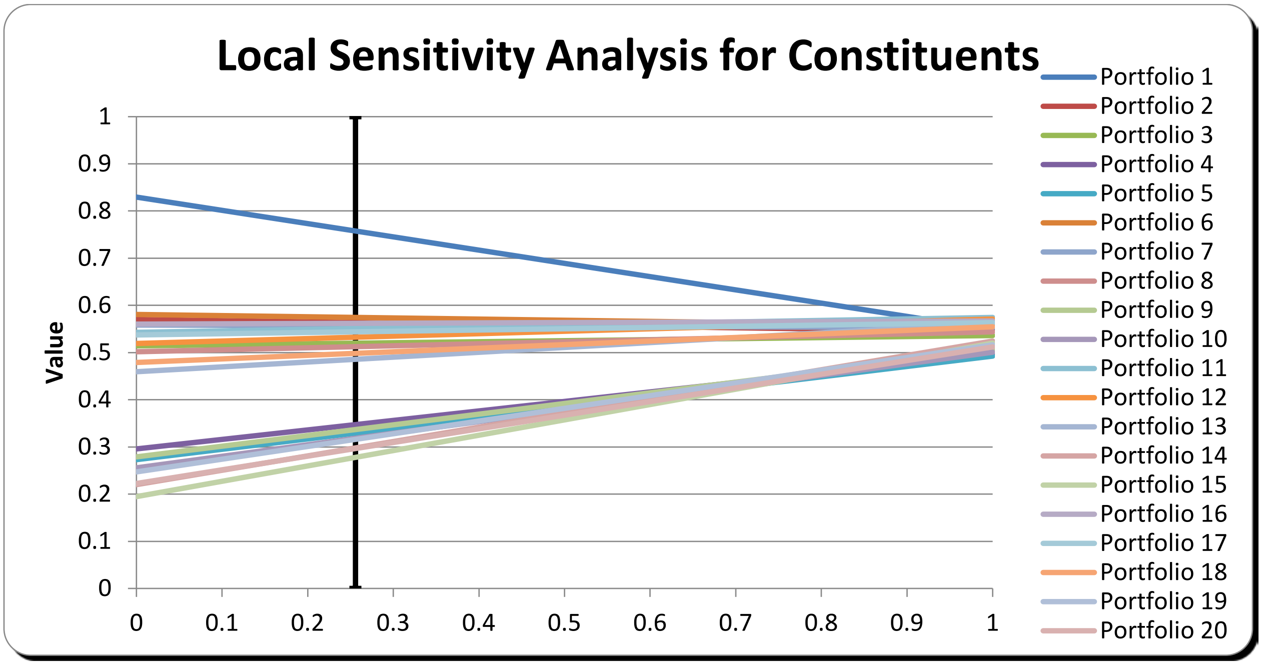
v. Minimize Permanent Soil Disruption



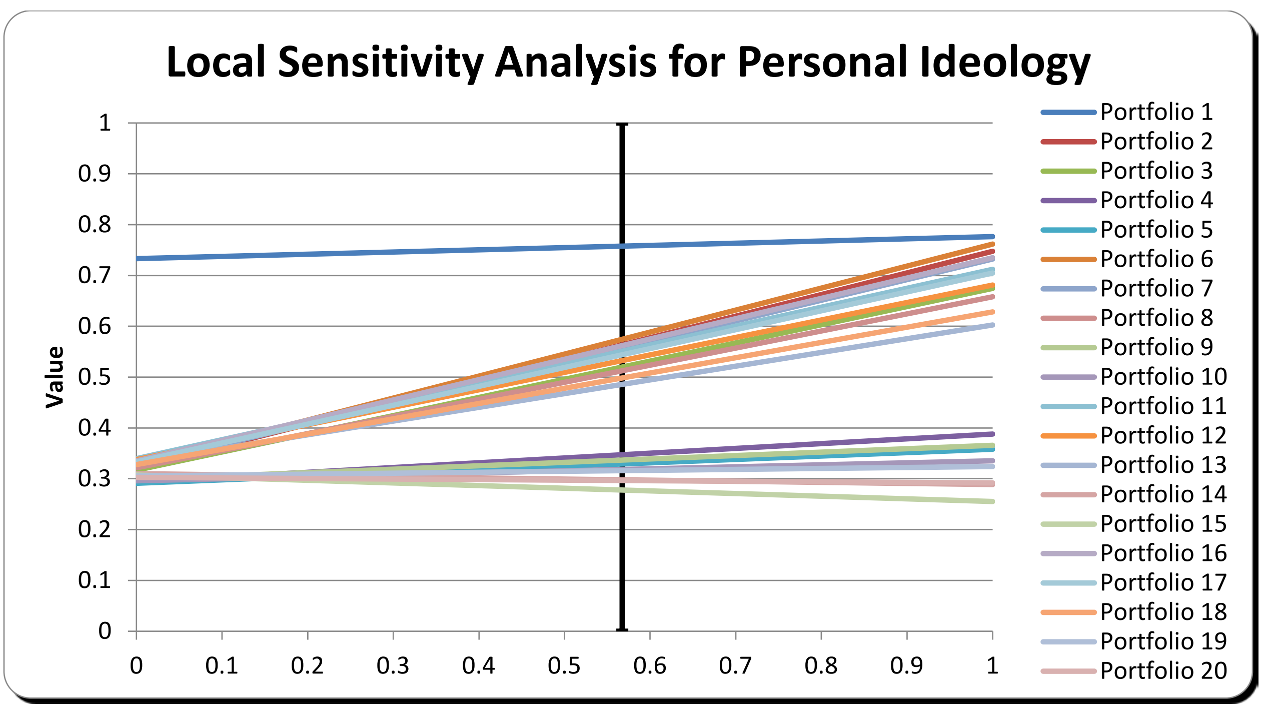
vi. Minimize Greenhouse Gas Emissions



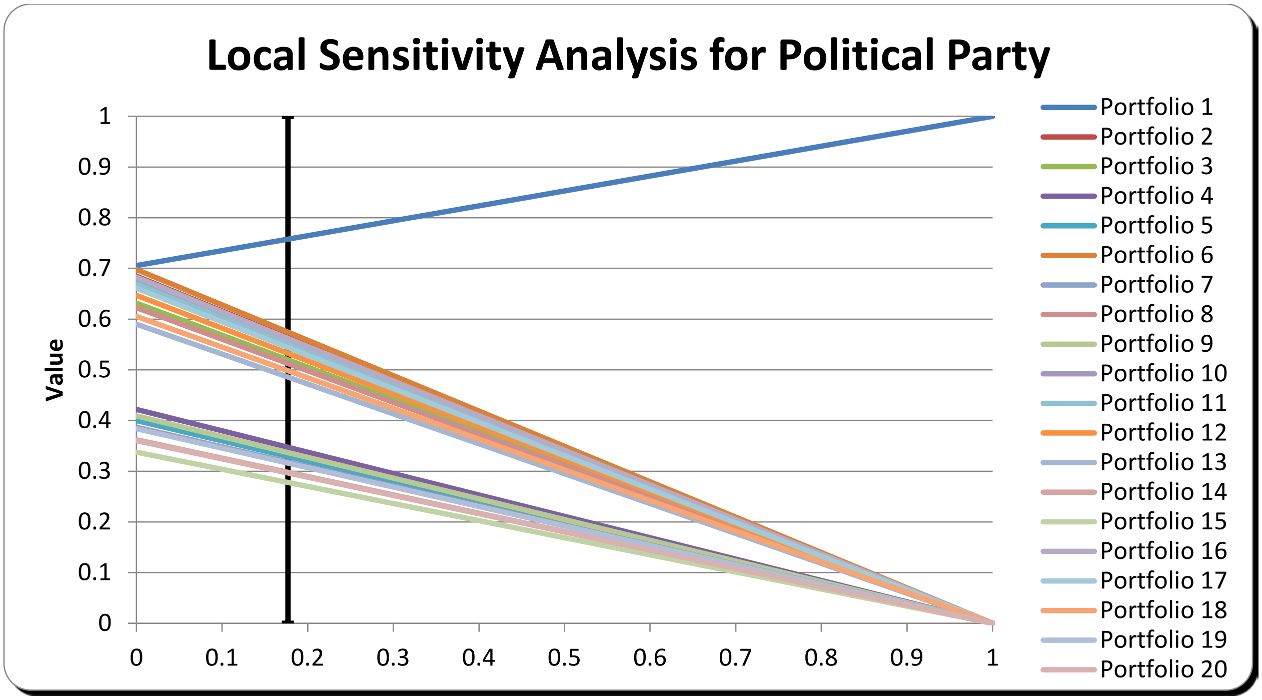
5. Silver Party DM # 5
    a. Local Sensitivity Graphs
        i. Constituent Satisfaction



        ii. Personal Ideology

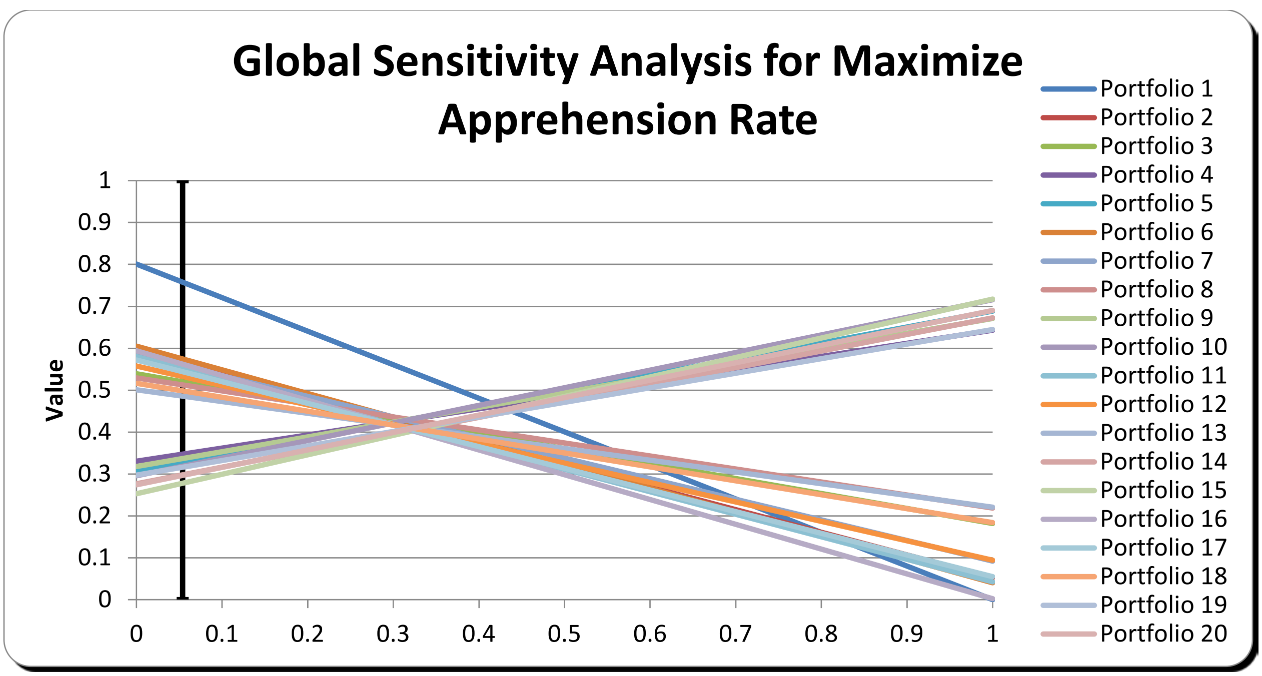


iii. Party Leader Support

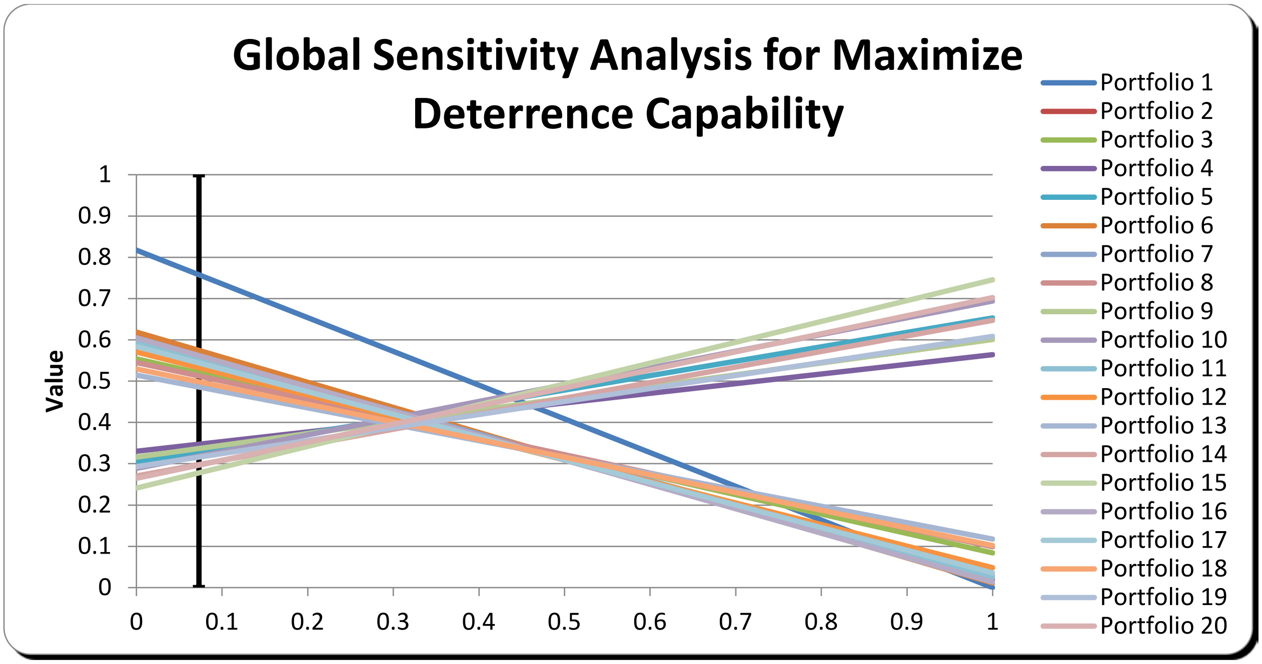


b. Global Sensitivity Graphs

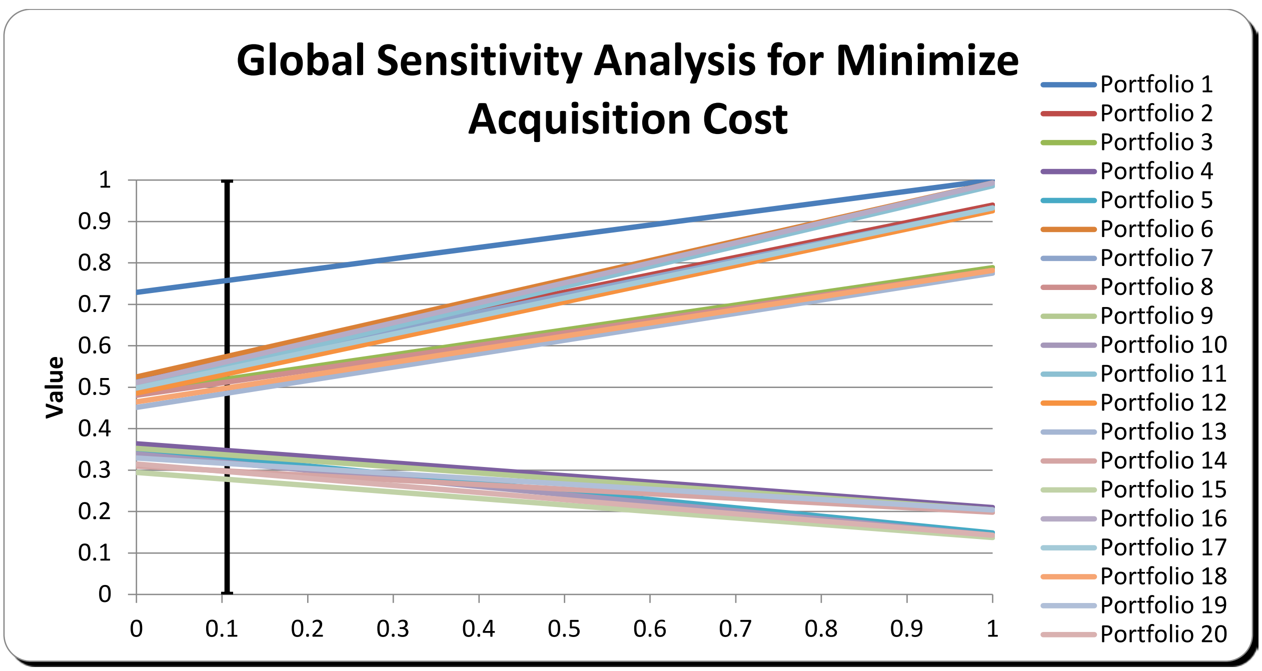
i. Maximize Apprehension Capability



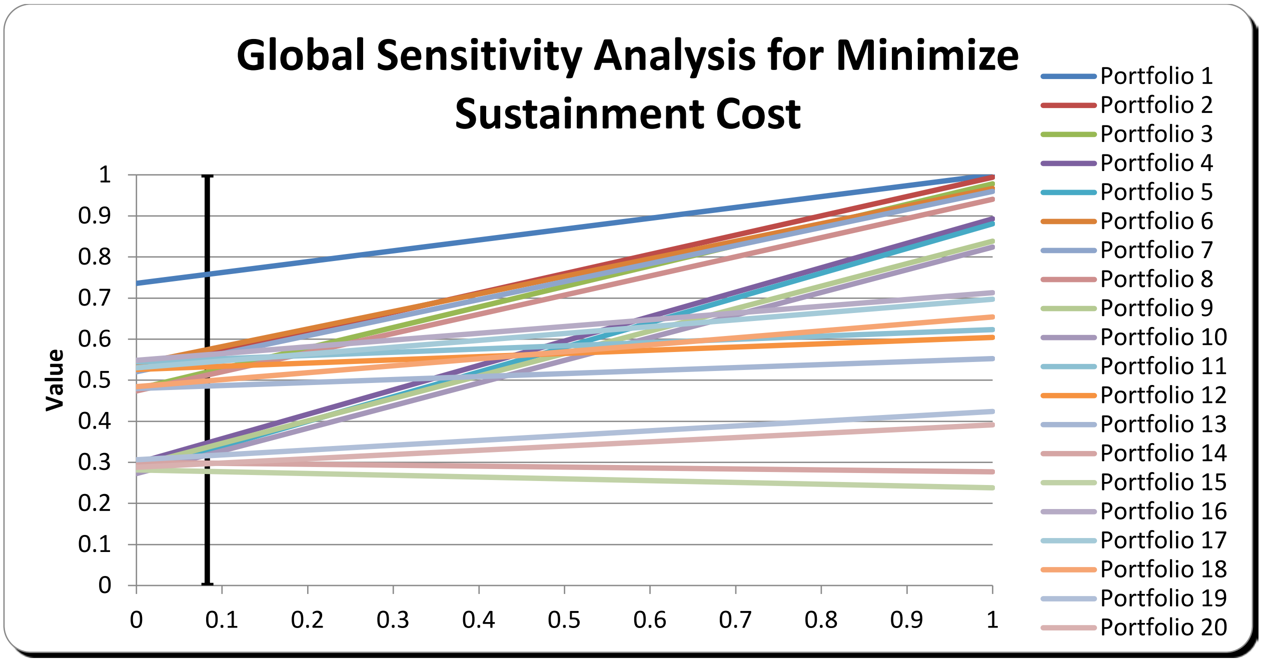
ii. Maximize Deterrence Capability



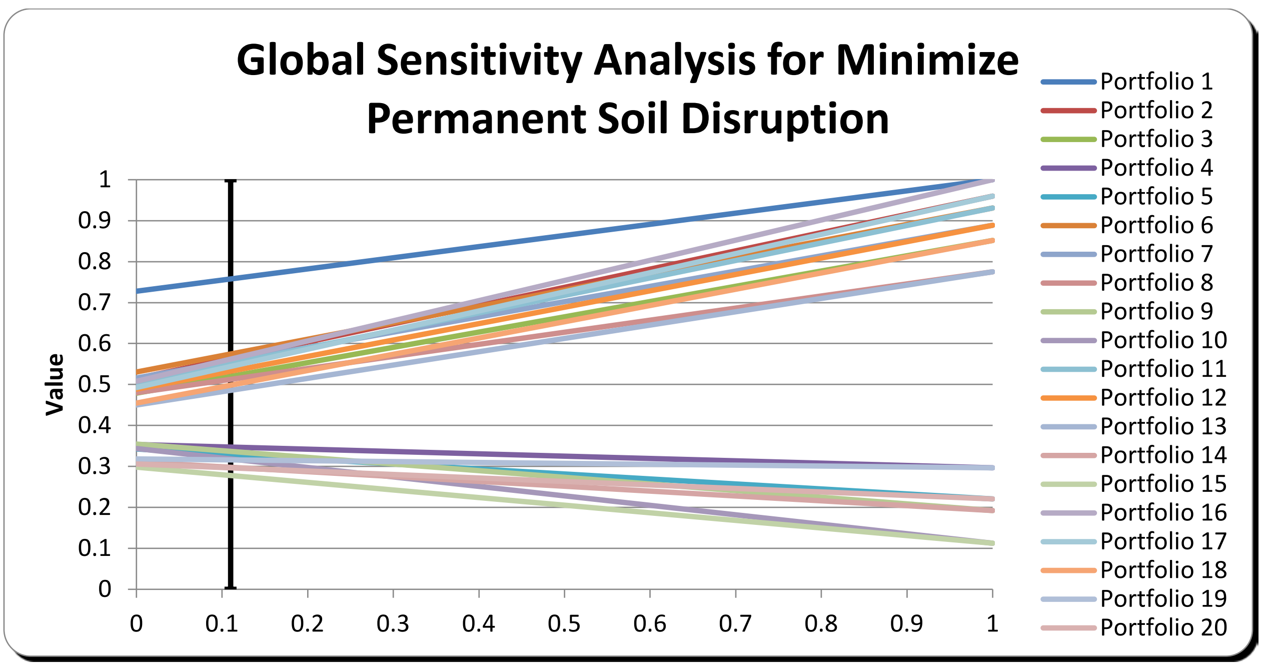
iii. Minimize Acquisition Cost



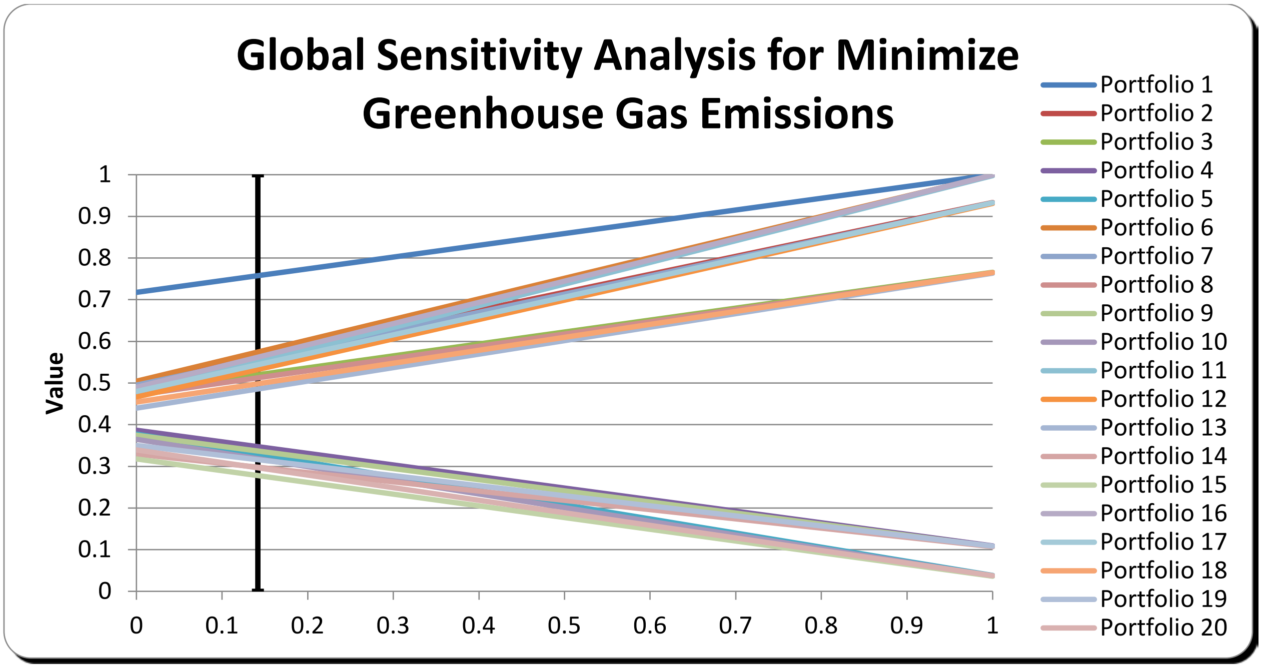
iv. Minimize Sustainment Cost



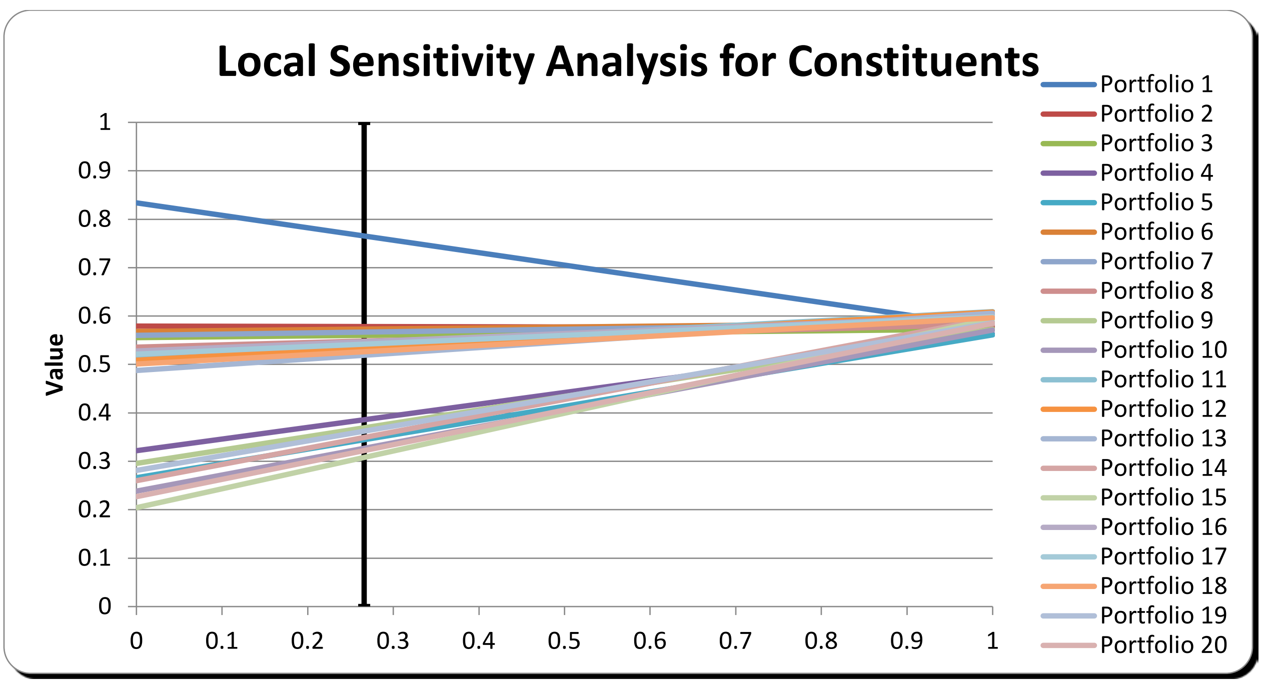
v. Minimize Permanent Soil Disruption



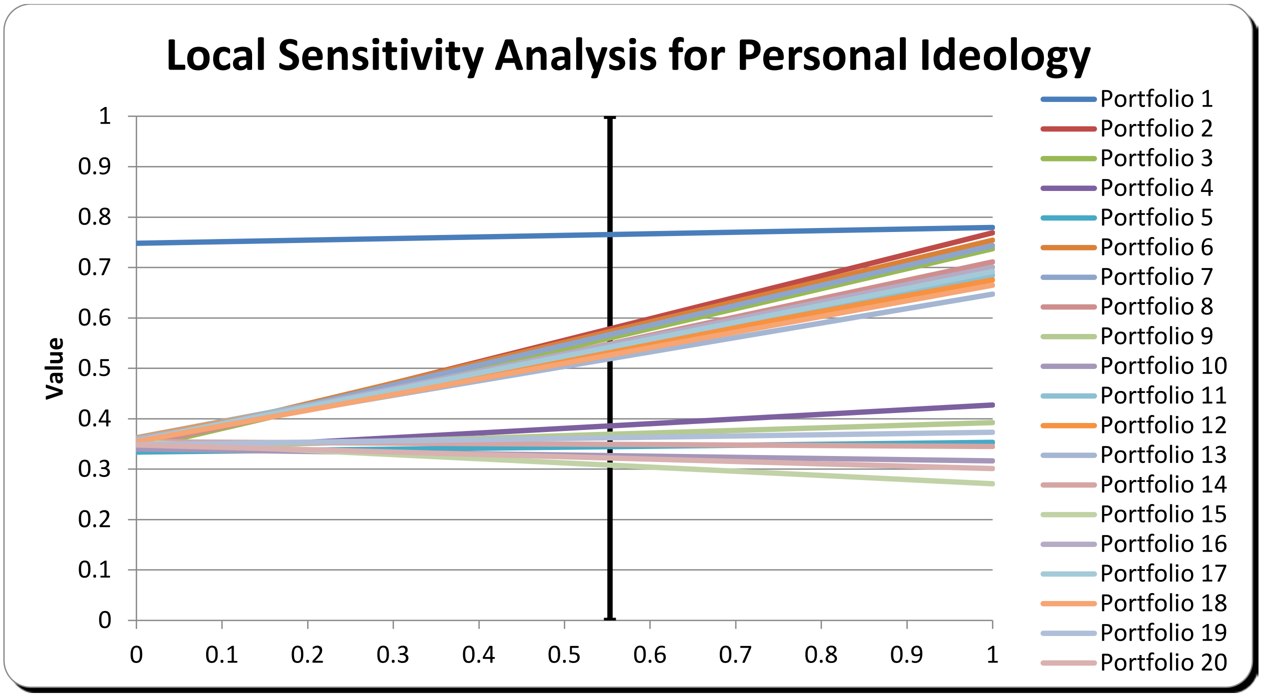
vi. Minimize Greenhouse Gas Emissions



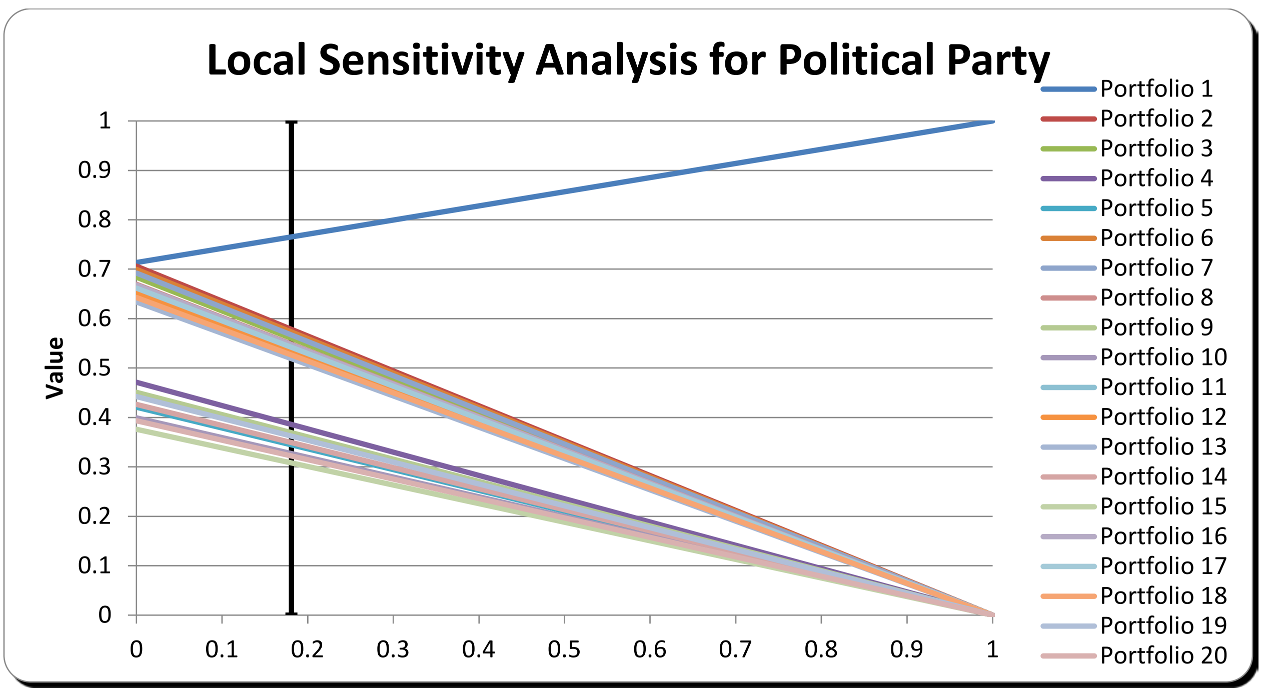
6. Silver Party DM # 6
   a. Local Sensitivity Graphs
      i. Constituent Satisfaction



ii. Personal Ideology

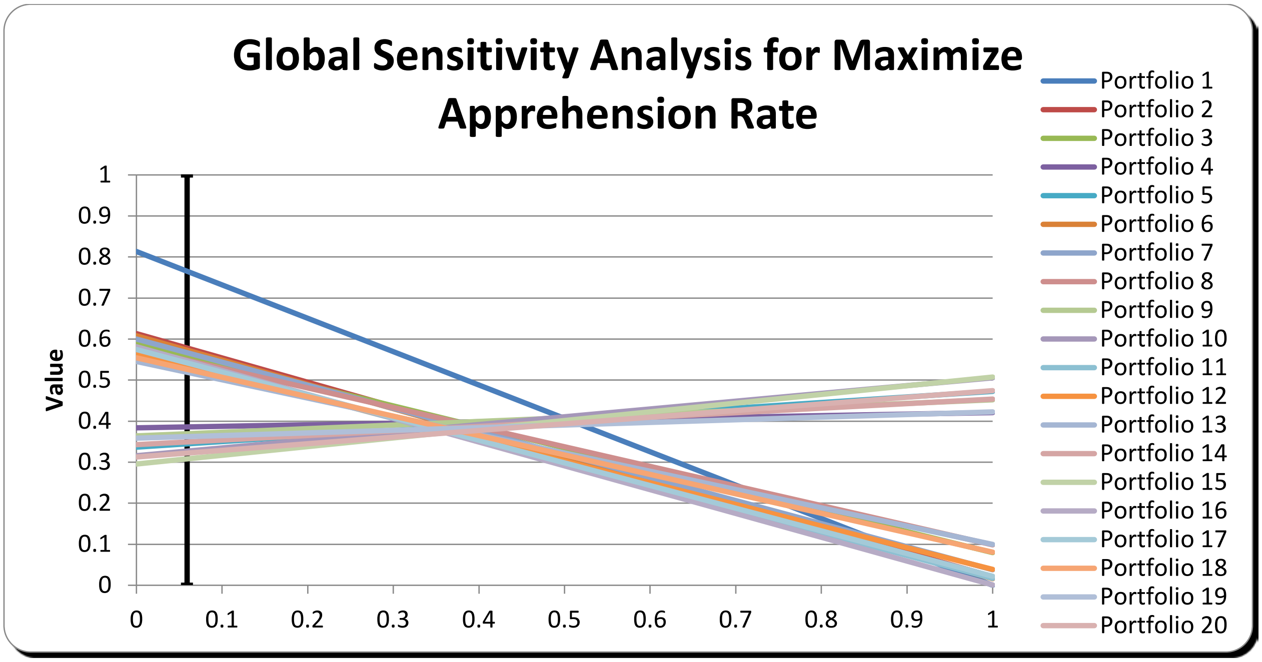


iii. Party Leader Support

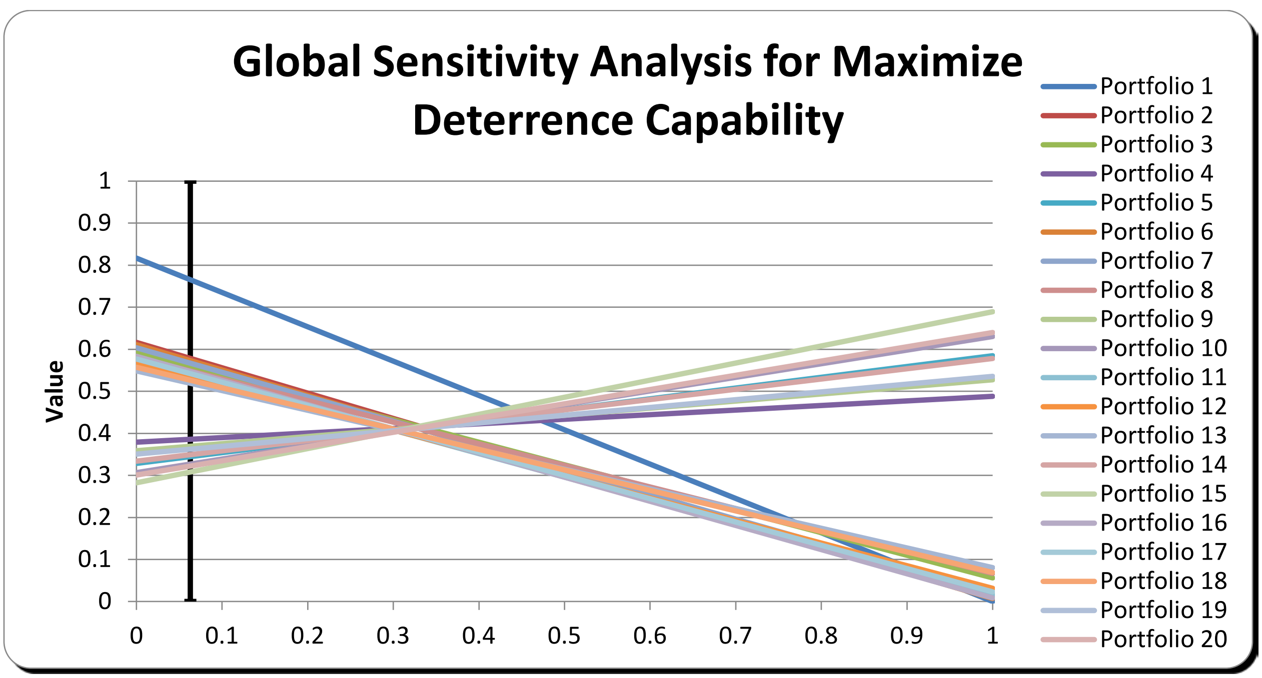


b. Global Sensitivity Graphs

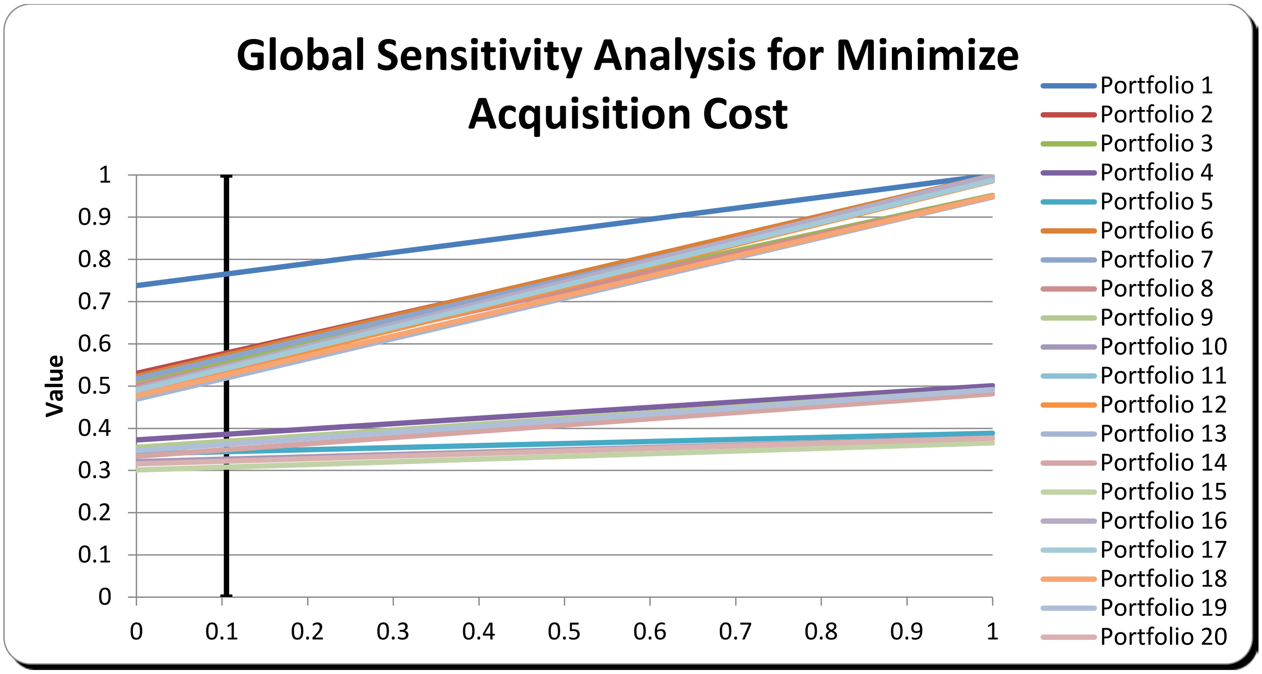
i. Maximize Apprehension Capability



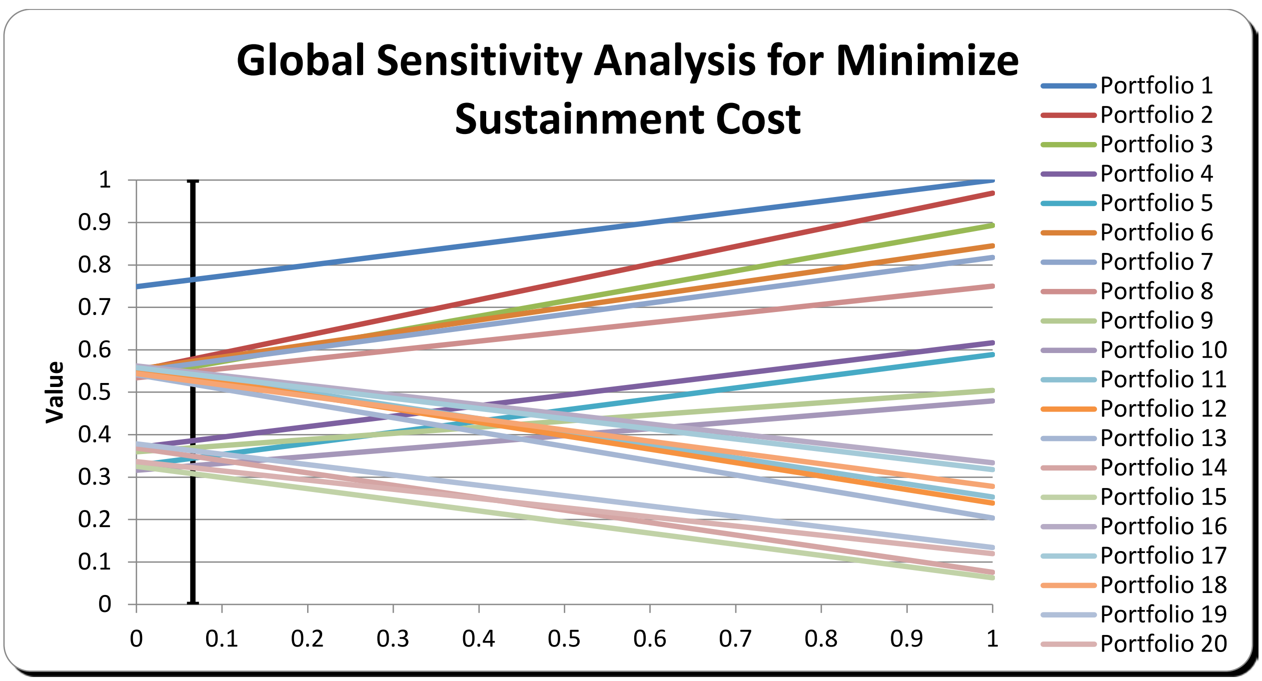
ii. Maximize Deterrence Capability



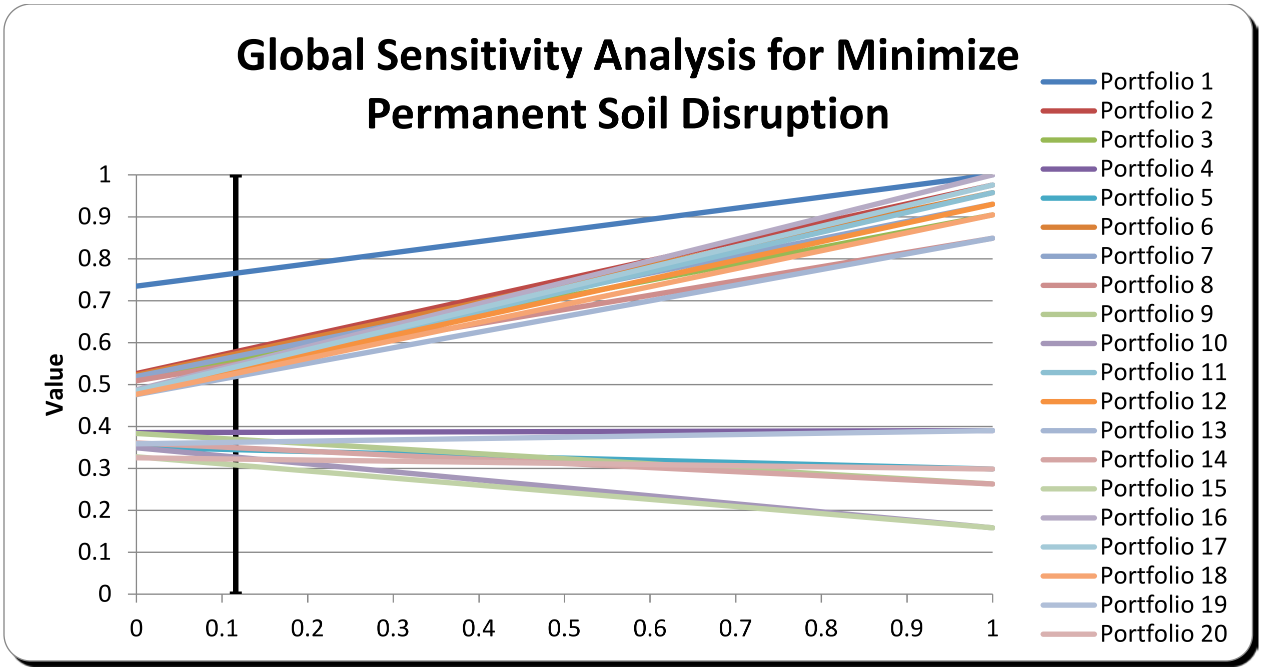
iii. Minimize Acquisition Cost



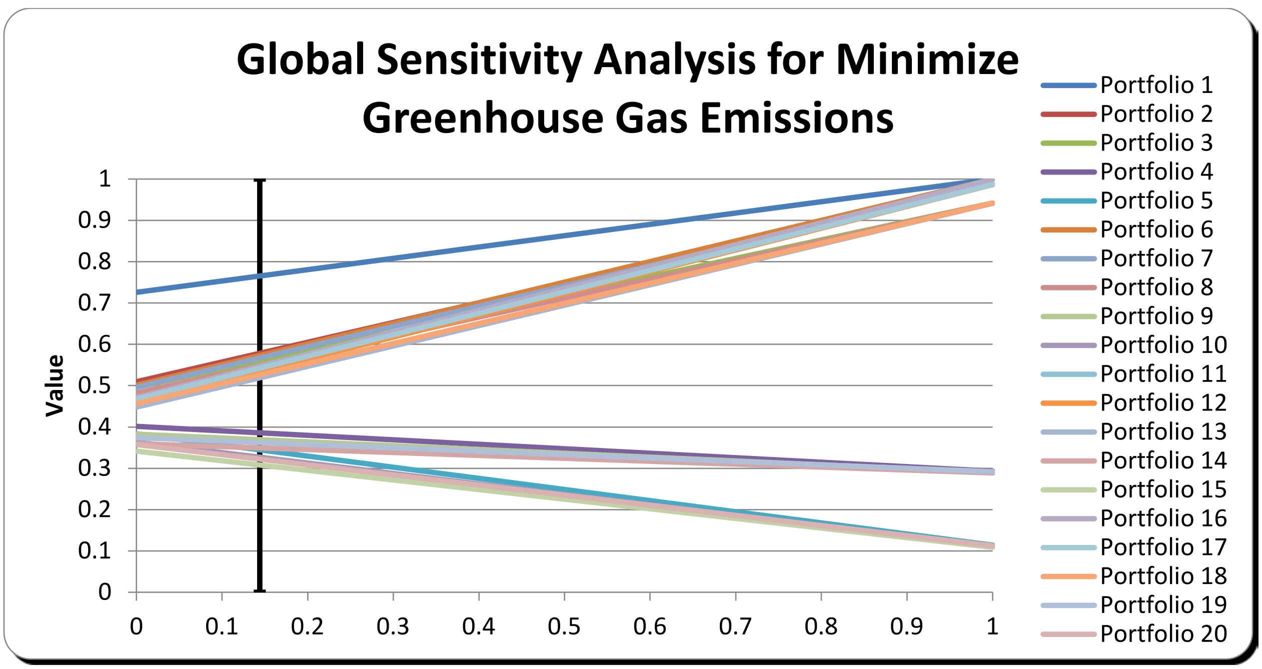
iv. Minimize Sustainment Cost



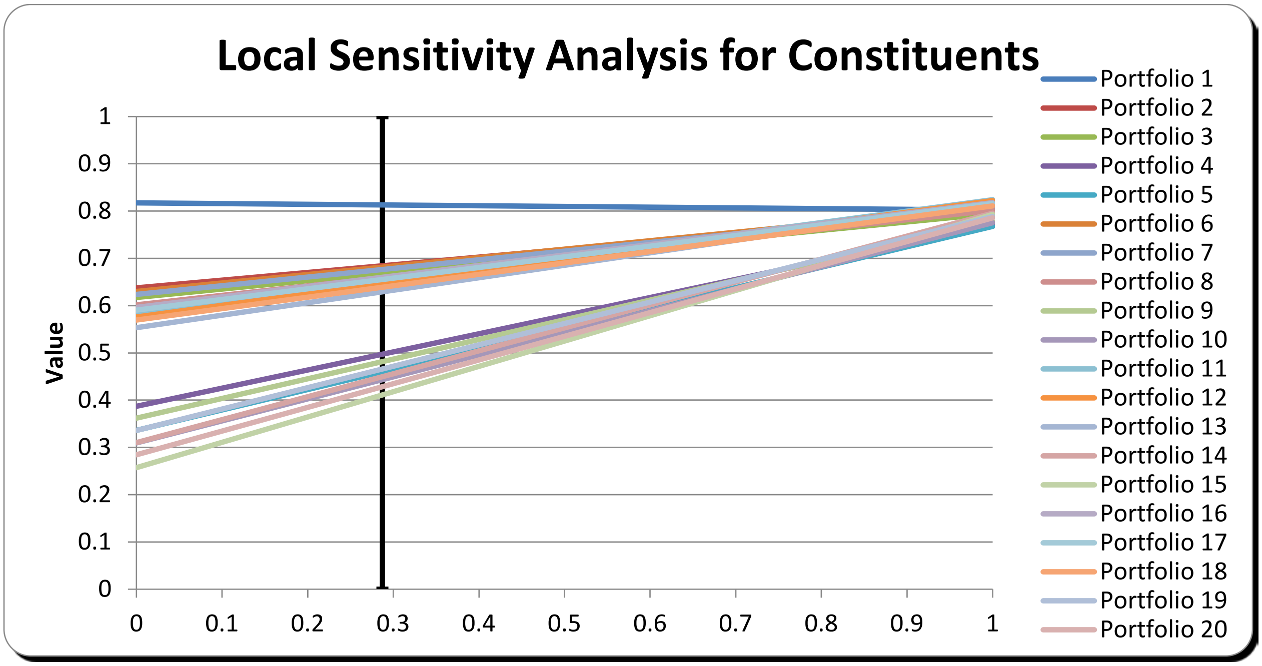
v. Minimize Permanent Soil Disruption



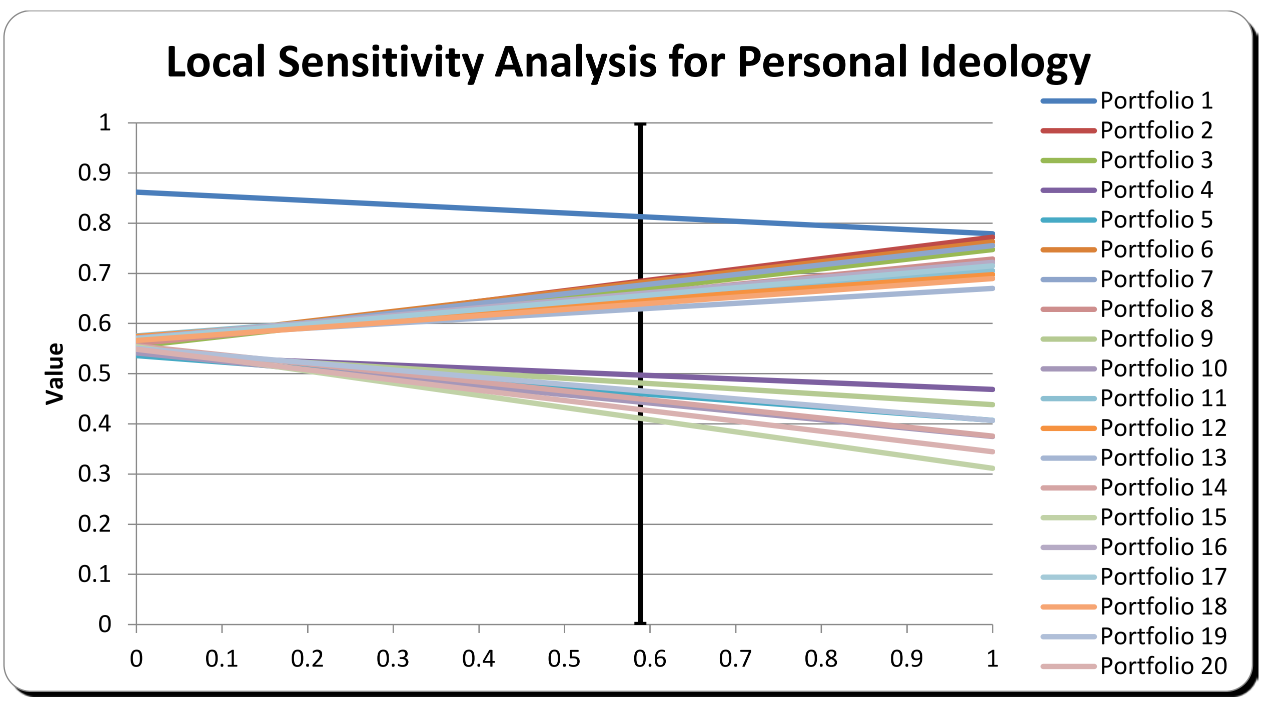
vi. Minimize Greenhouse Gas Emissions



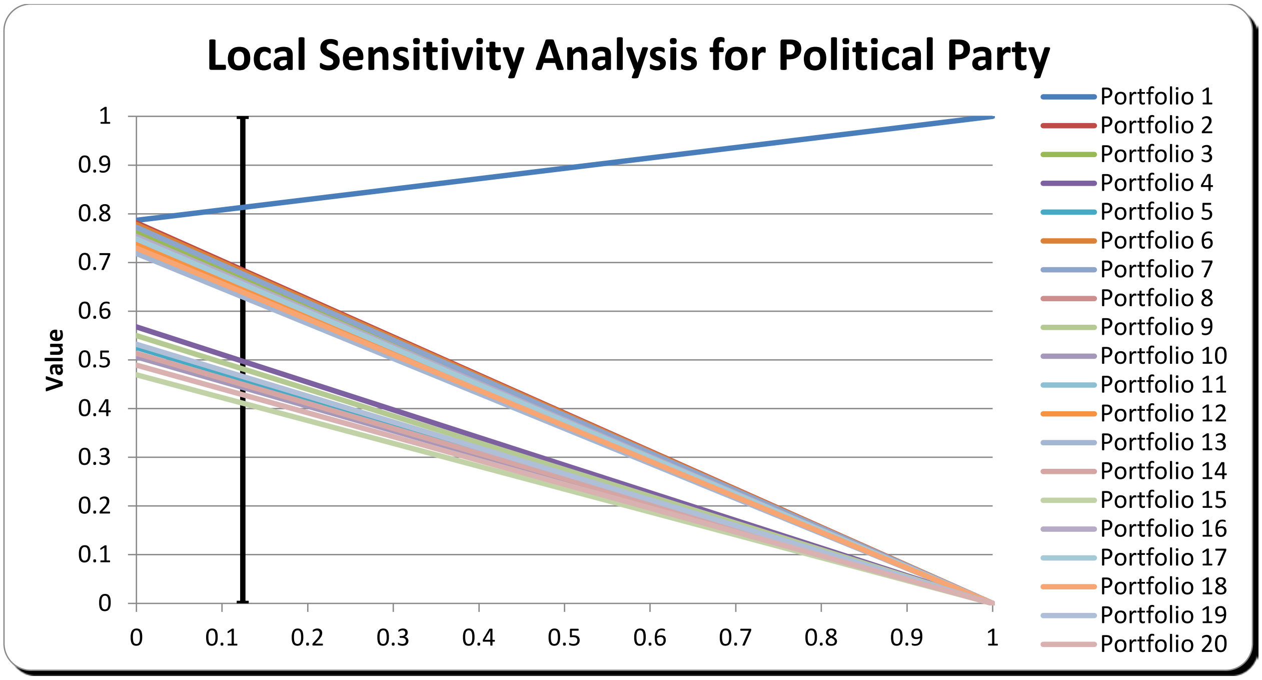
7. Silver Party DM # 7
    a. Local Sensitivity Graphs
        i. Constituent Satisfaction



        ii. Personal Ideology

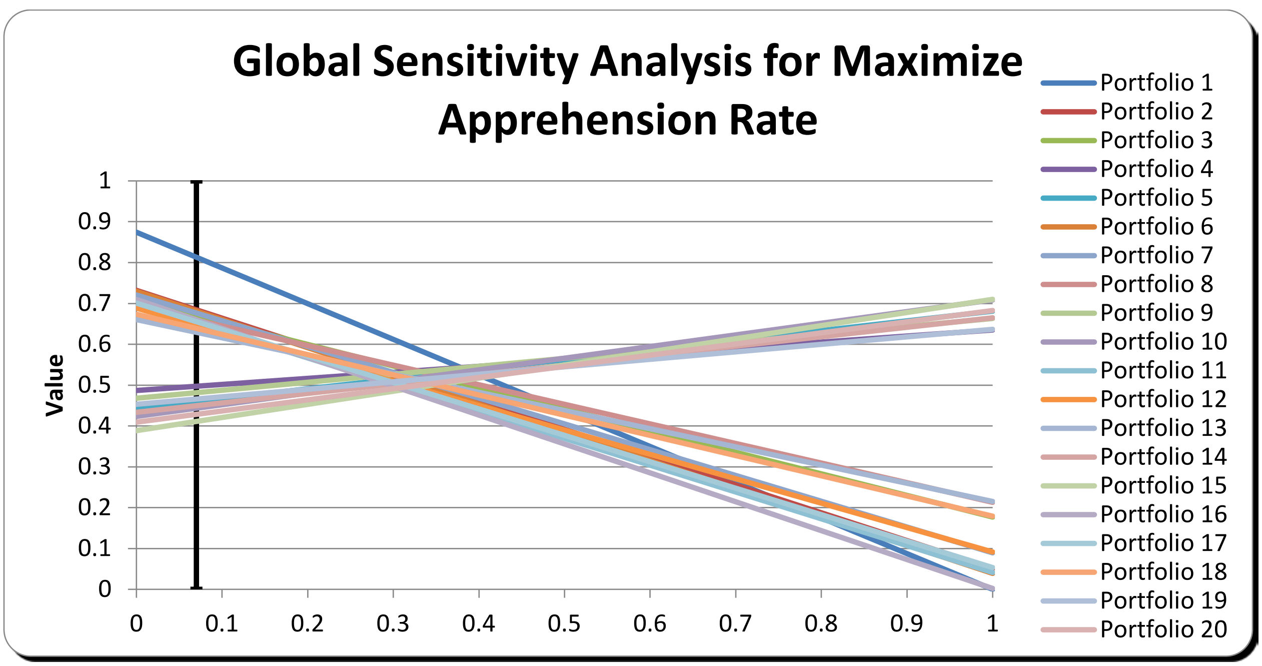


iii. Party Leader Support

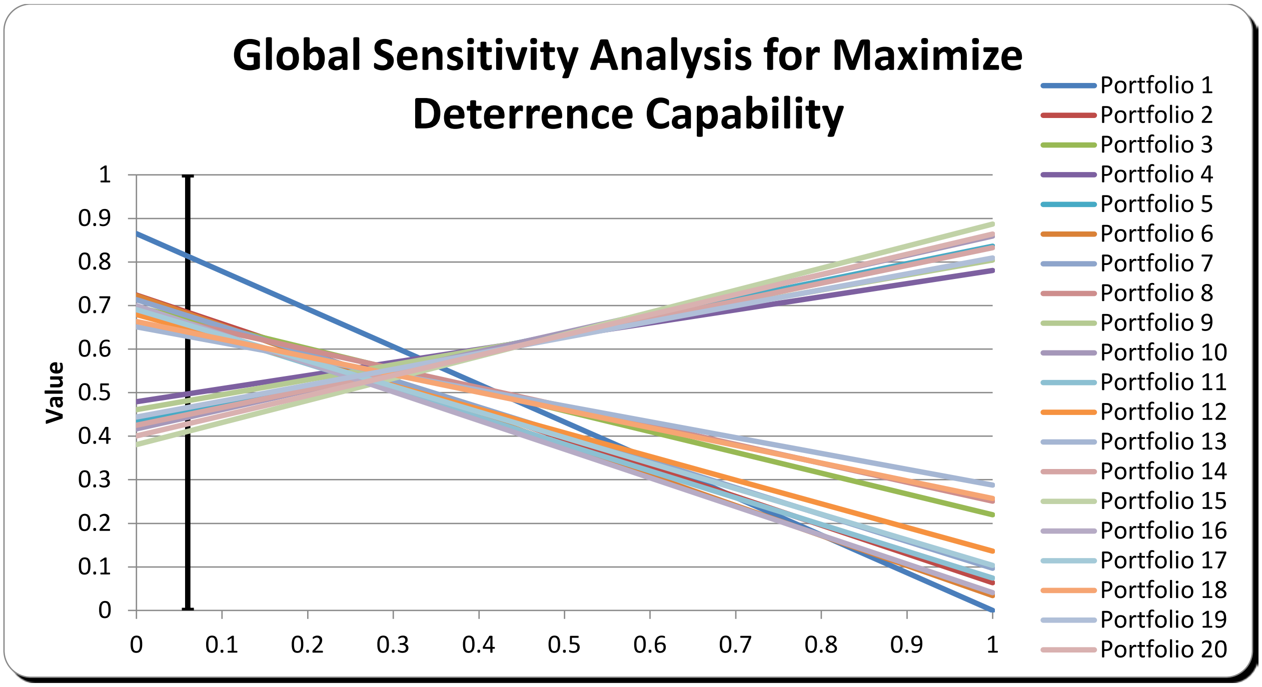


b. Global Sensitivity Graphs

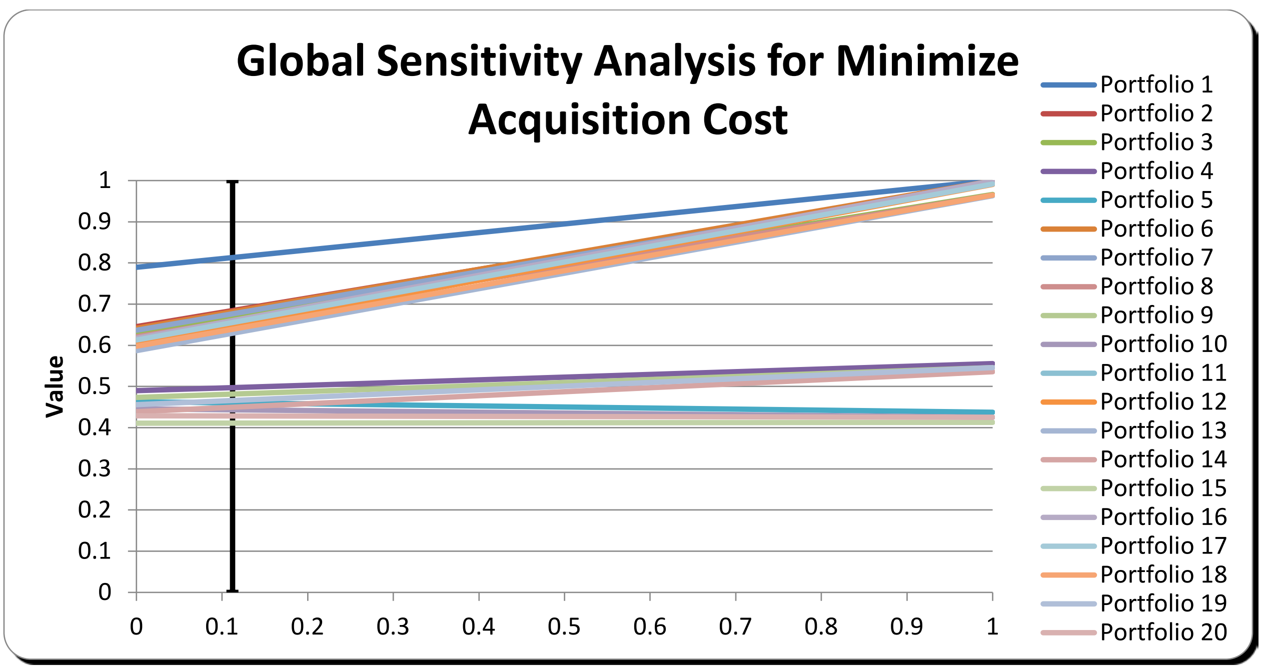
i. Maximize Apprehension Capability



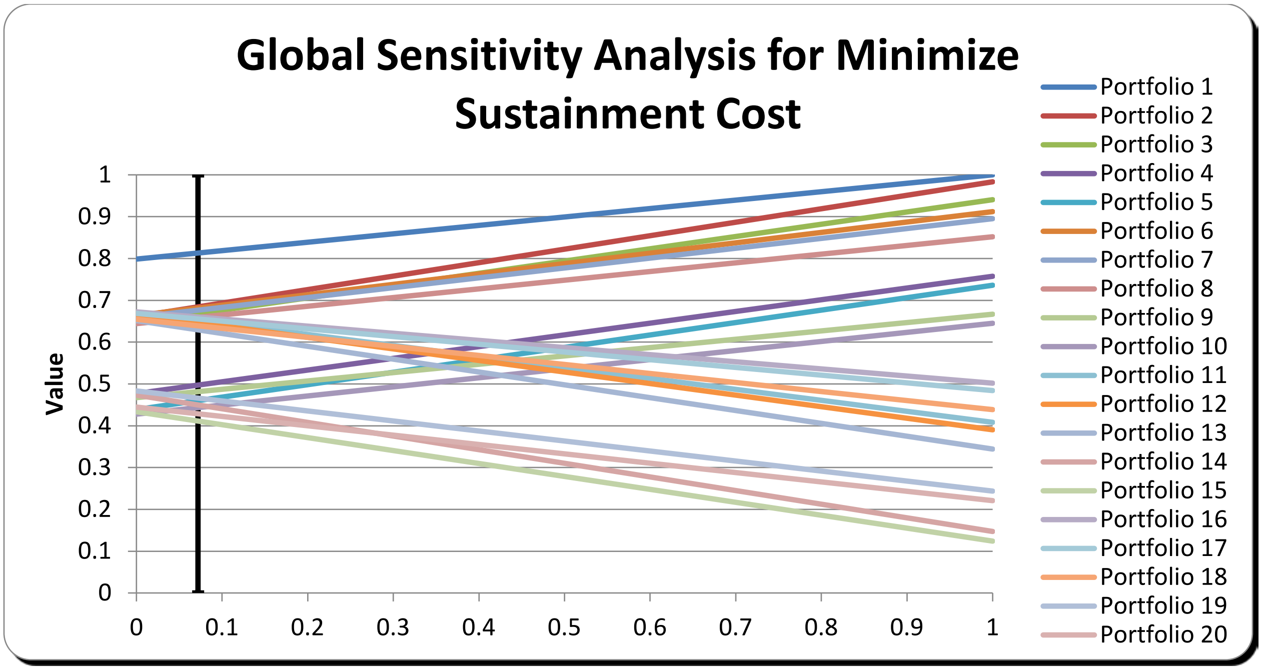
ii. Maximize Deterrence Capability



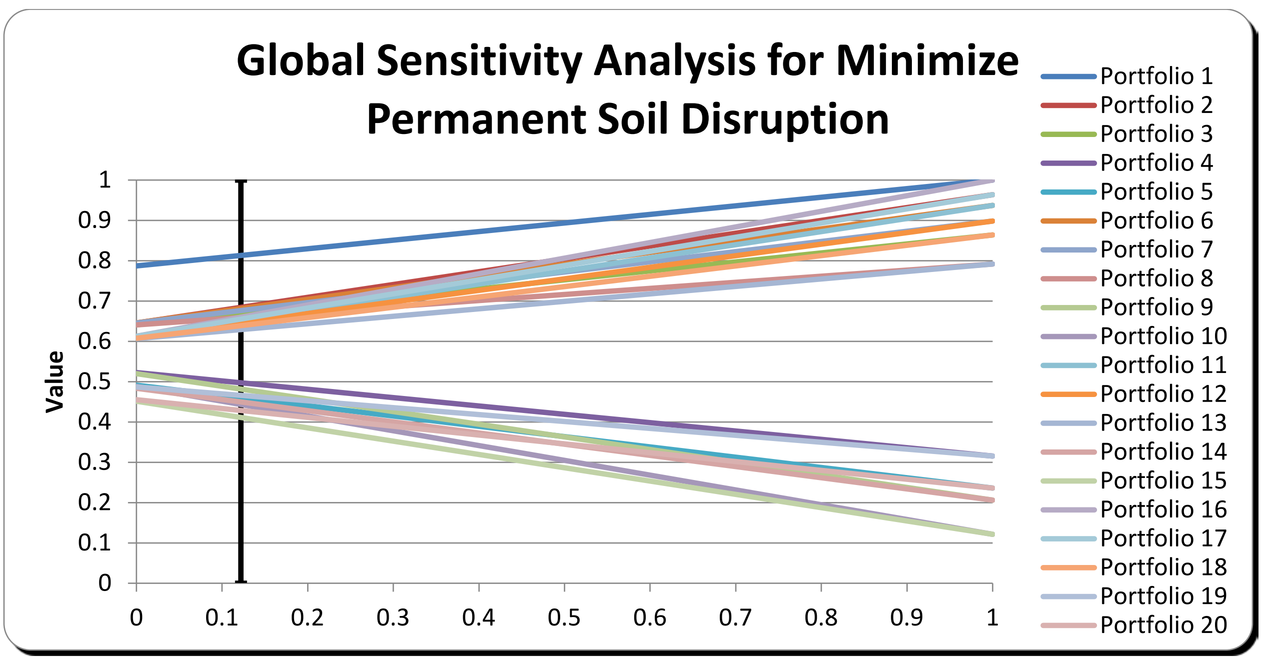
iii. Minimize Acquisition Cost



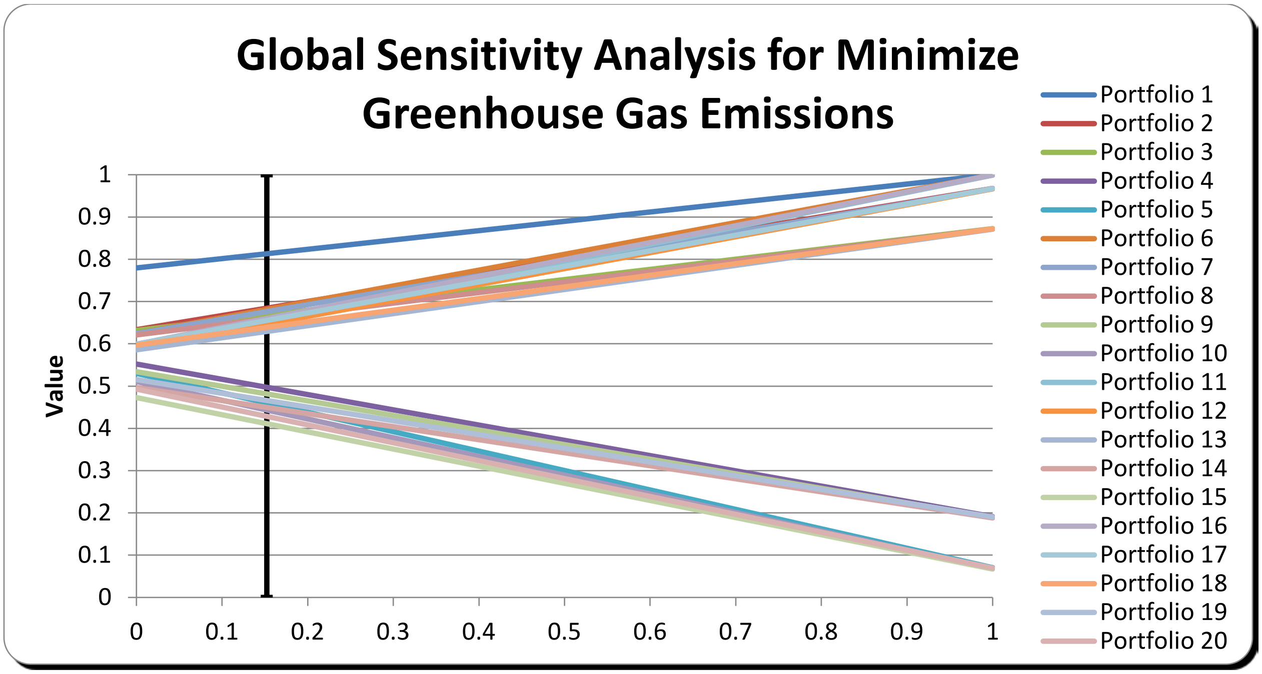
iv. Minimize Sustainment Cost



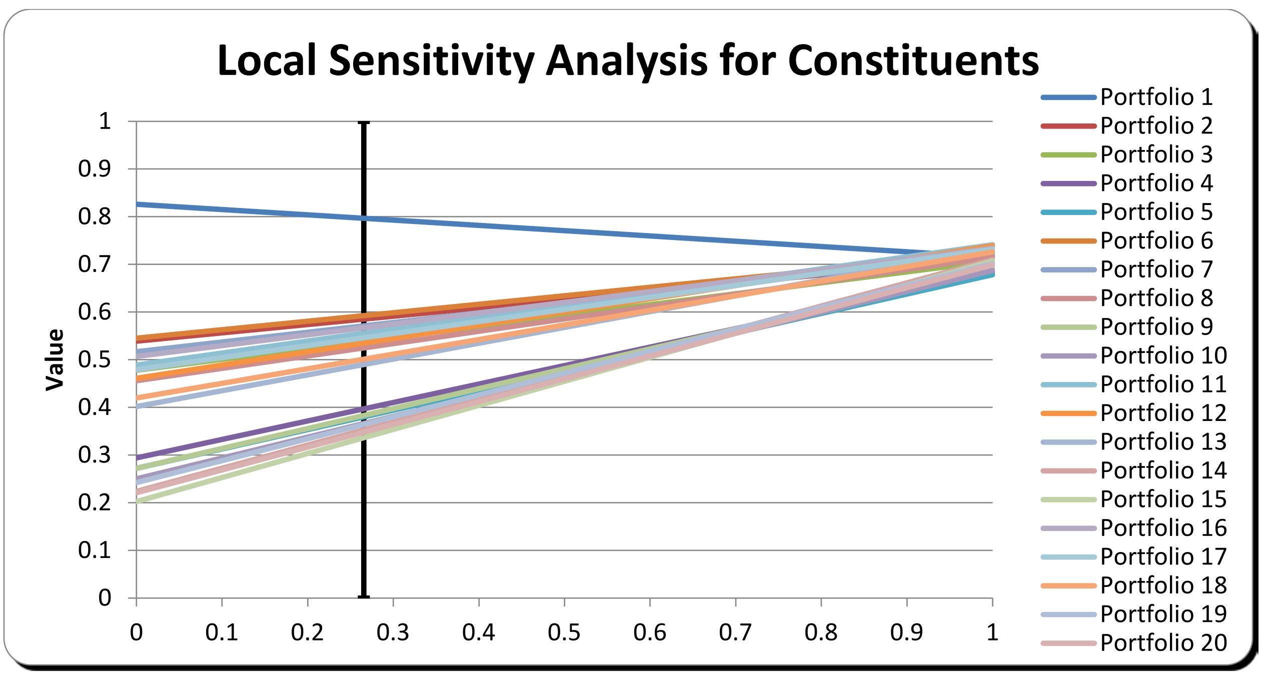
v. Minimize Permanent Soil Disruption



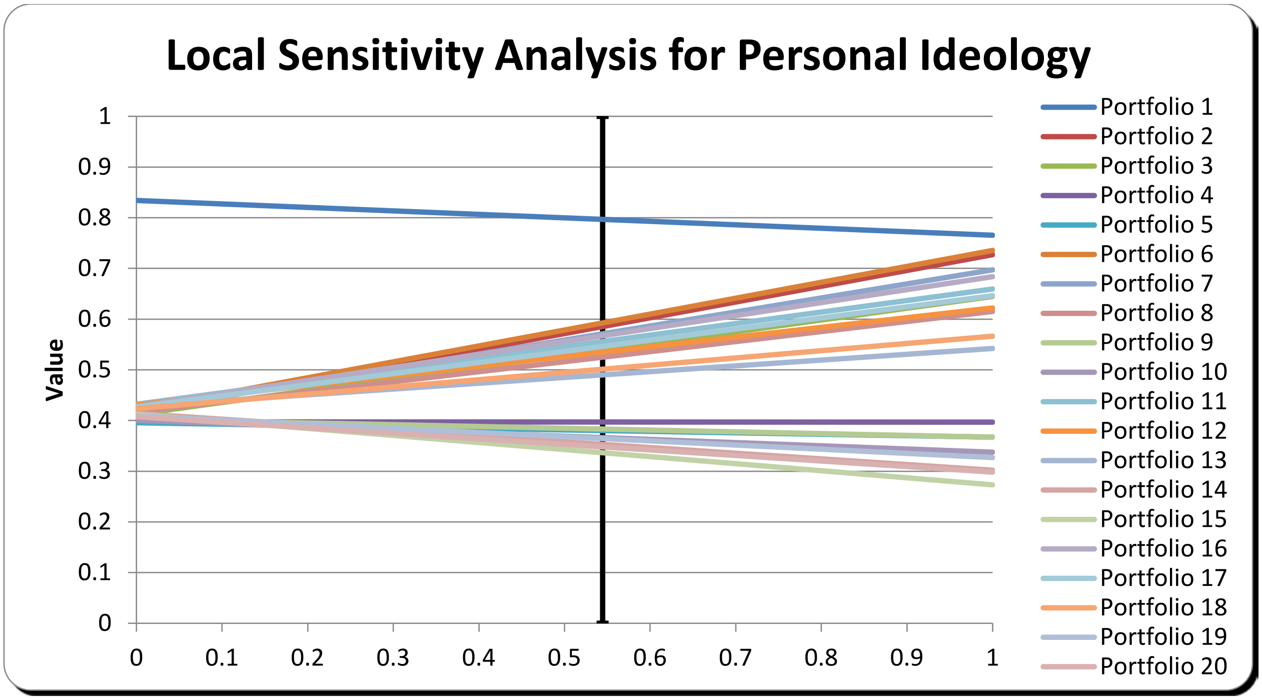
vi. Minimize Greenhouse Gas Emissions



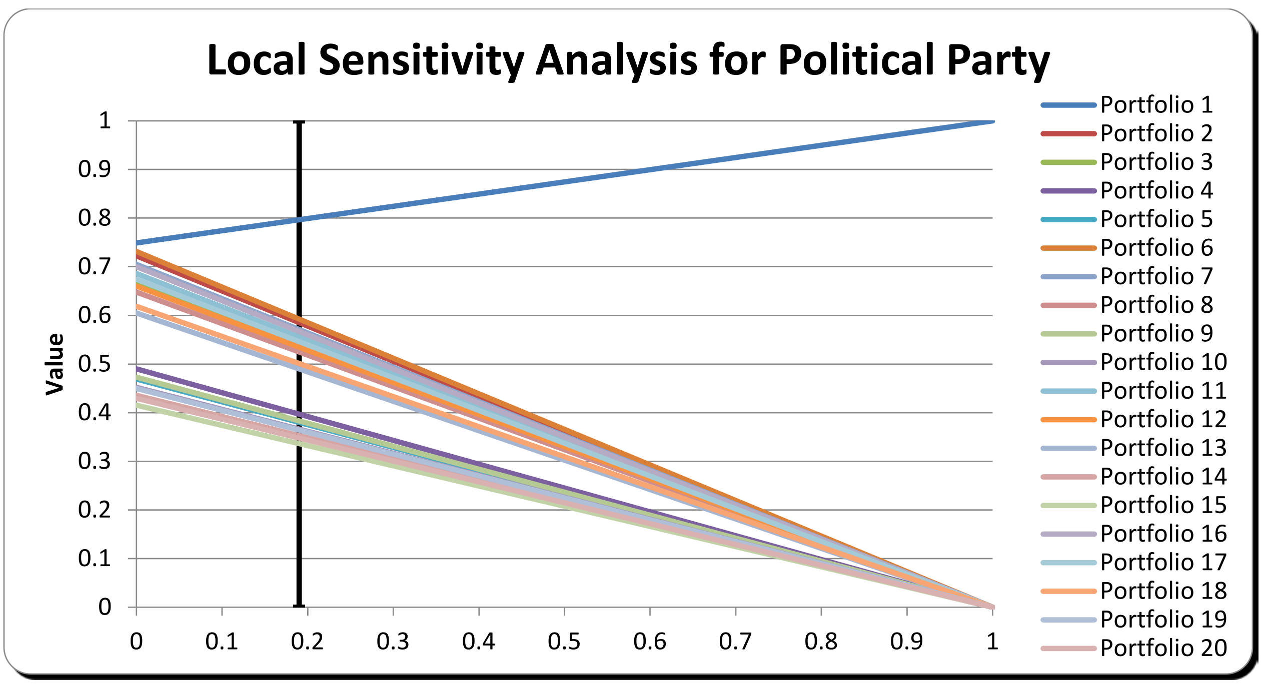
8. Silver Party DM # 8
   a. Local Sensitivity Graphs
      i. Constituent Satisfaction



ii. Personal Ideology

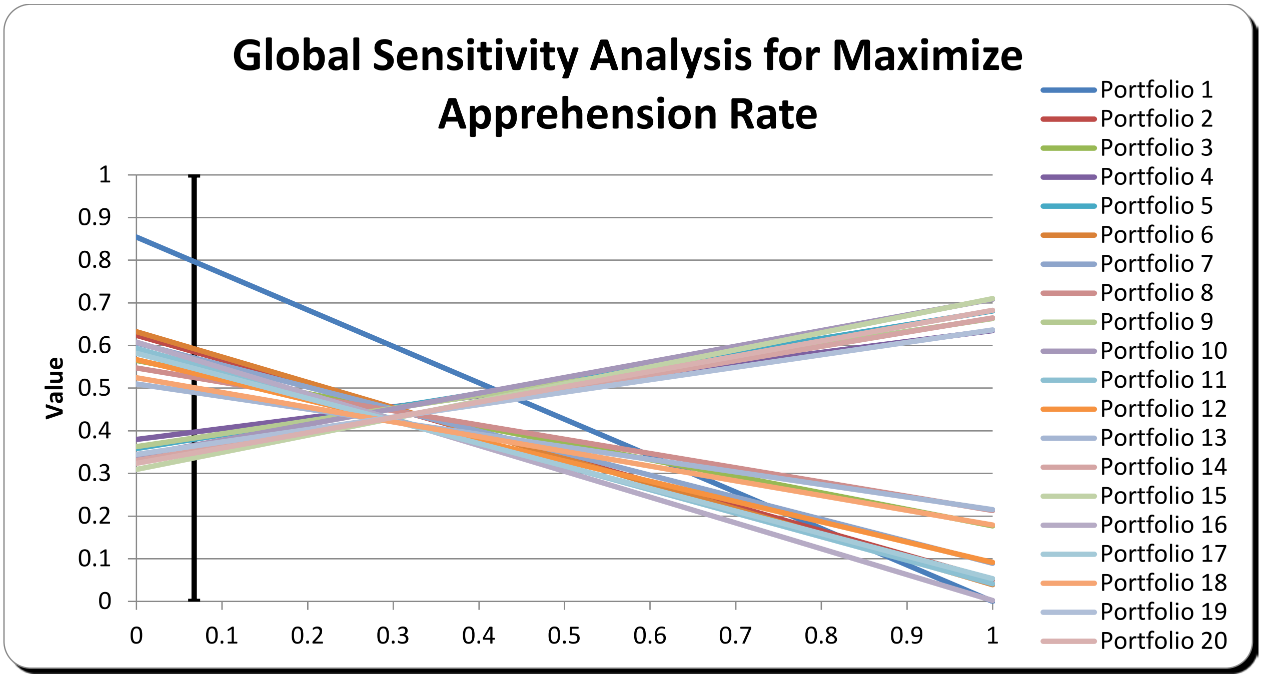


iii. Party Leader Support

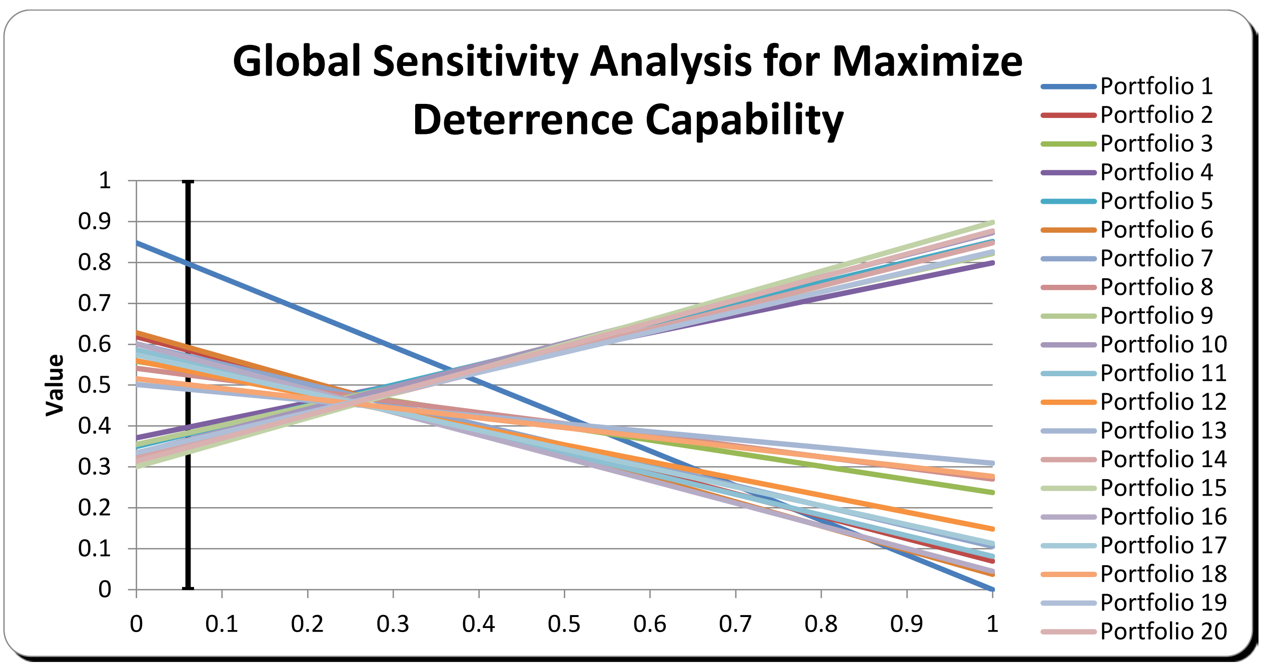


b. Global Sensitivity Graphs

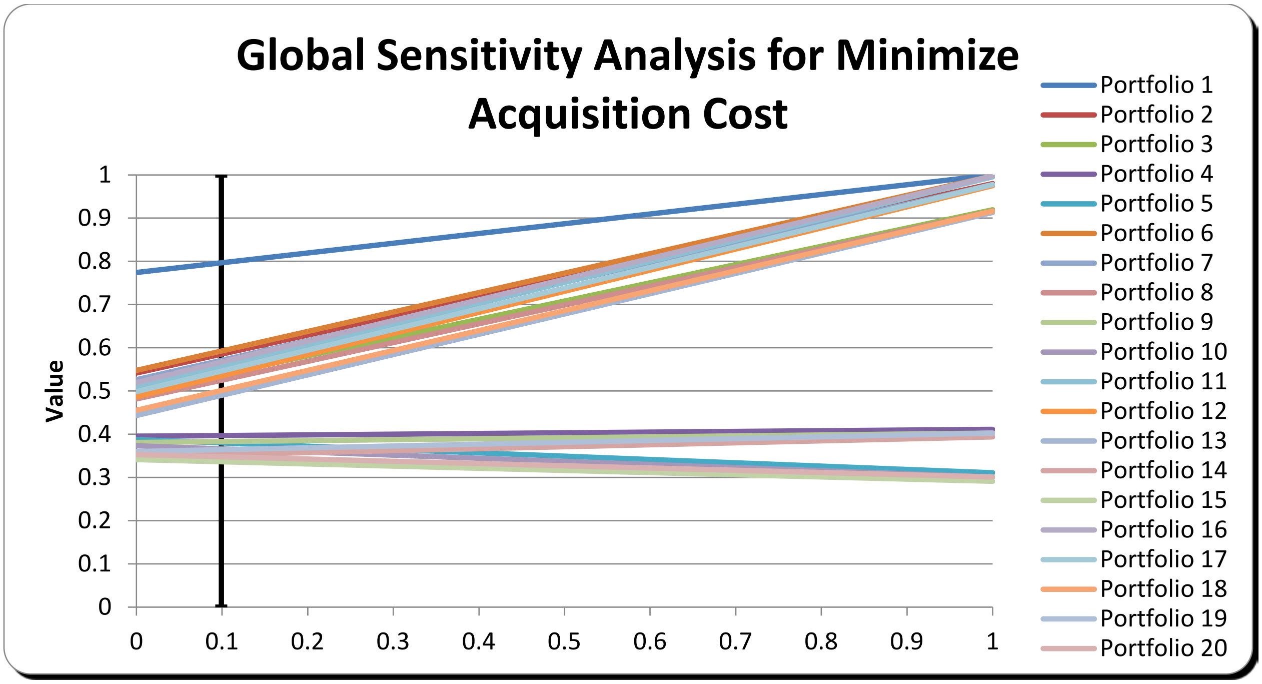
i. Maximize Apprehension Capability



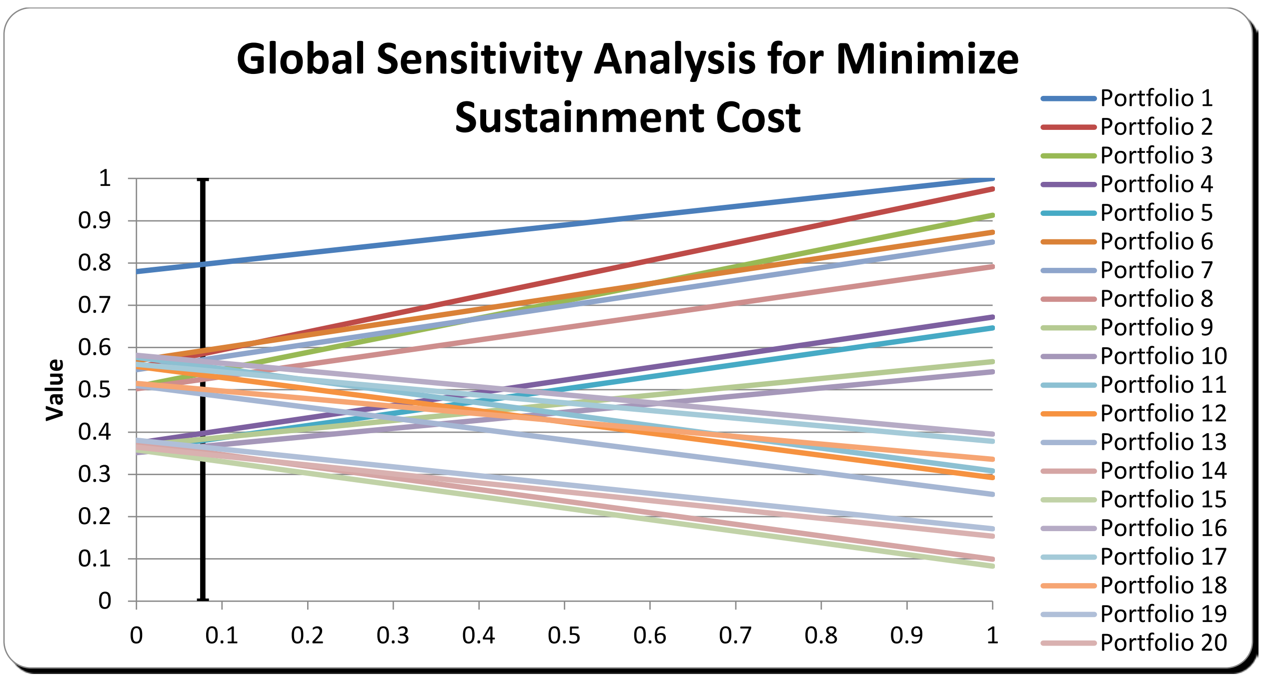
ii. Maximize Deterrence Capability



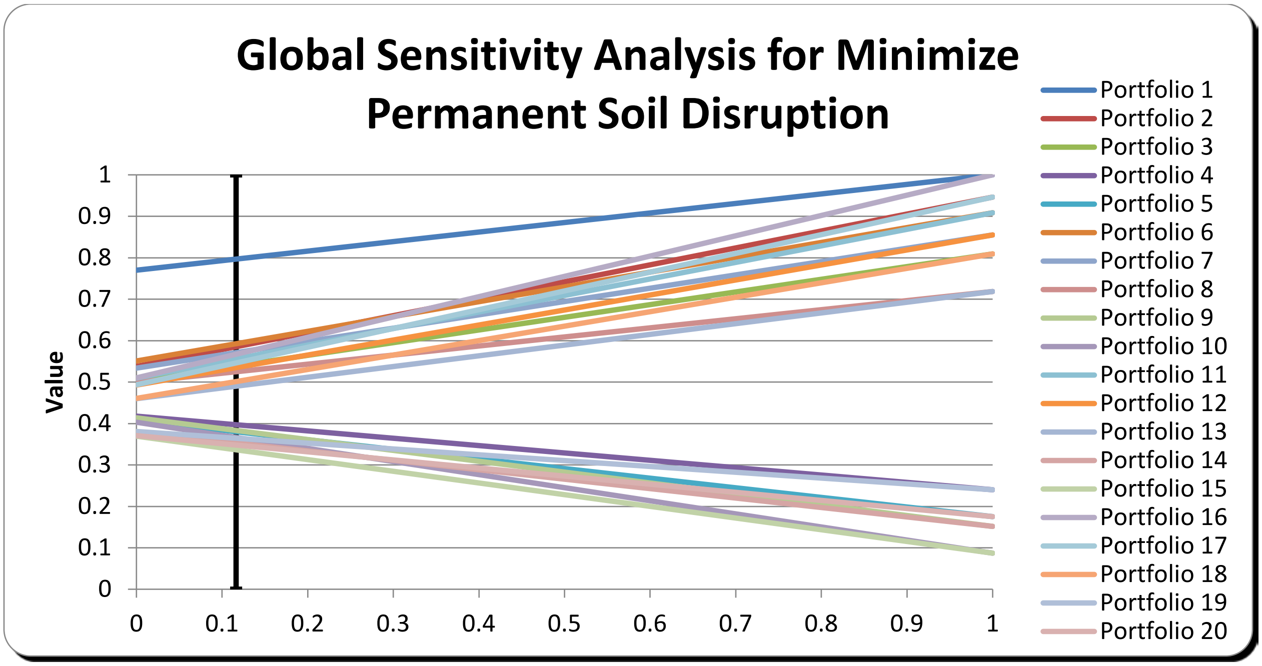
iii. Minimize Acquisition Cost



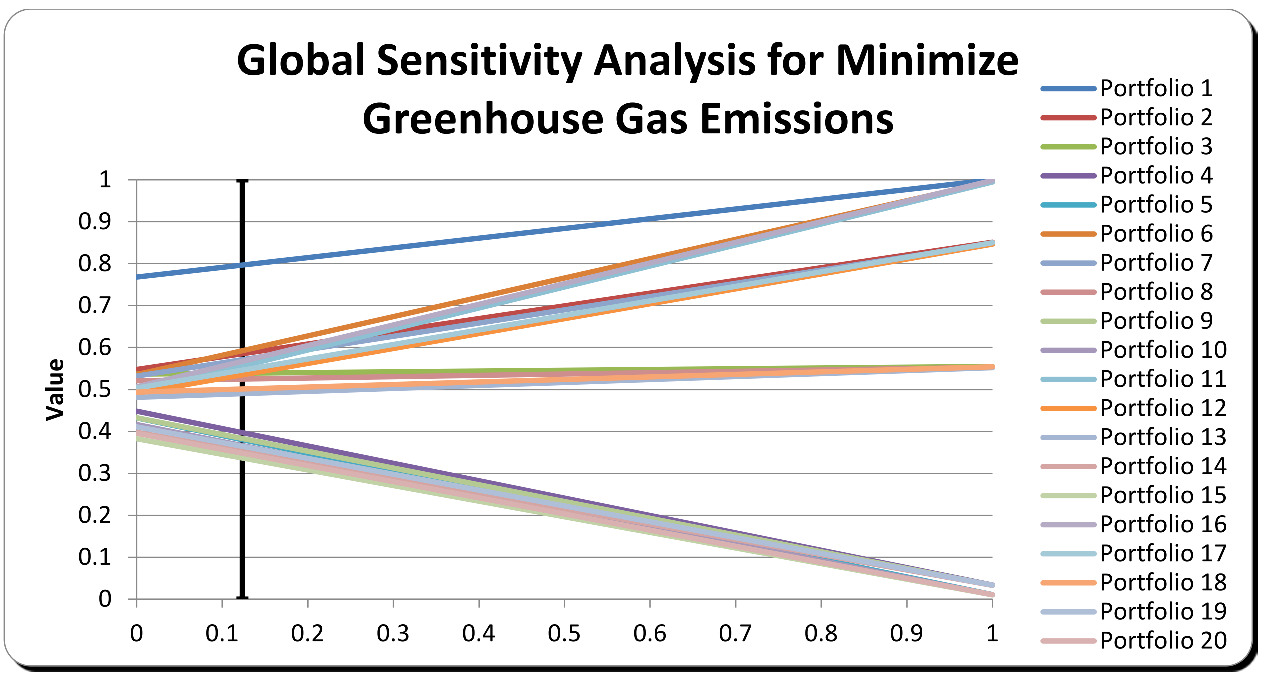
iv. Minimize Sustainment Cost



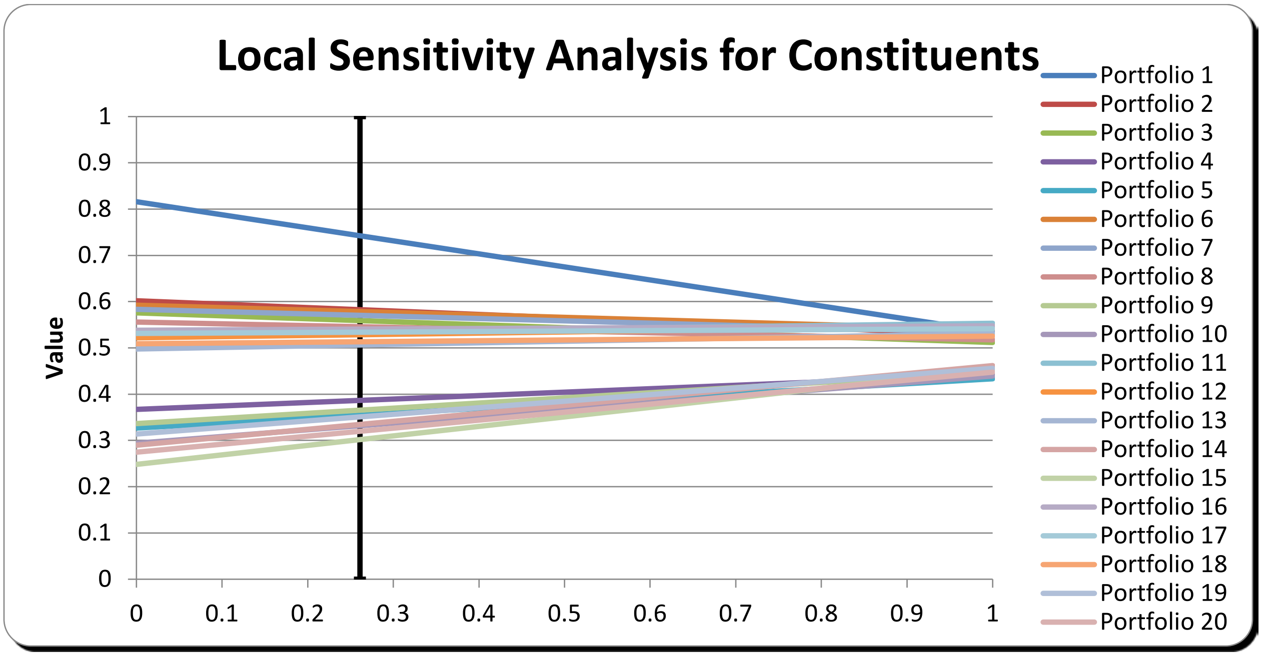
v. Minimize Permanent Soil Disruption



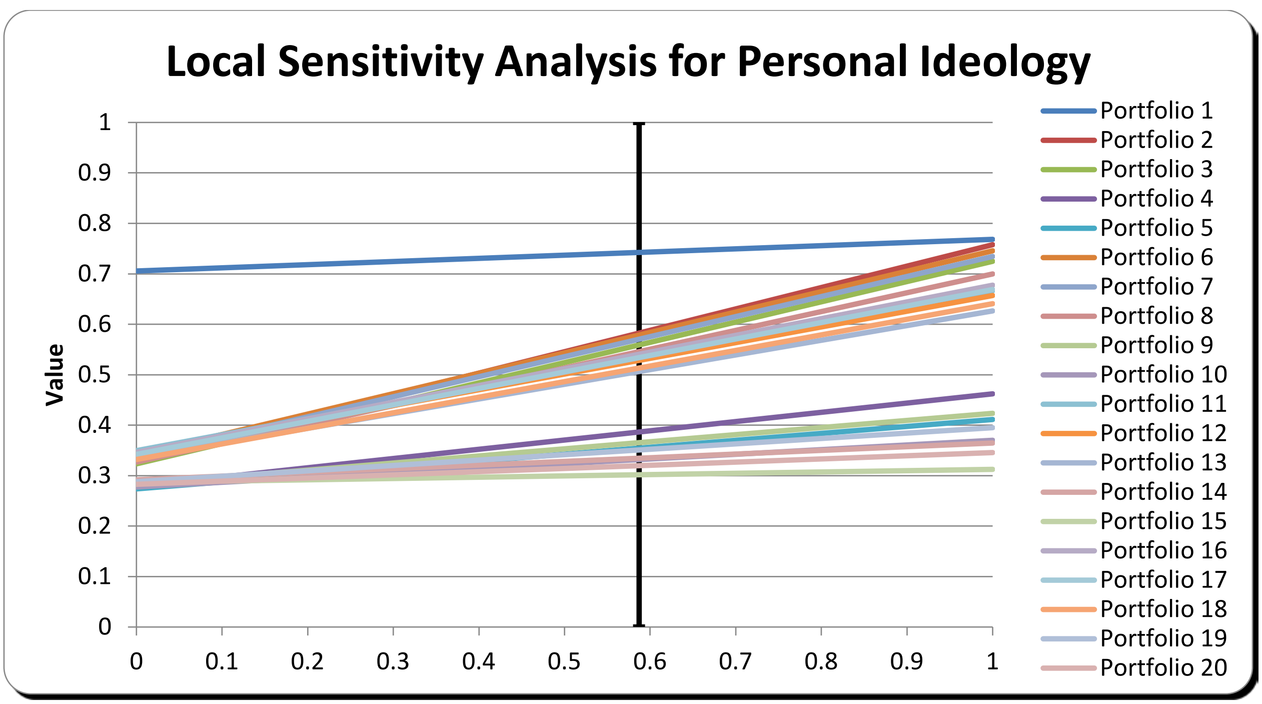
vi. Minimize Greenhouse Gas Emissions



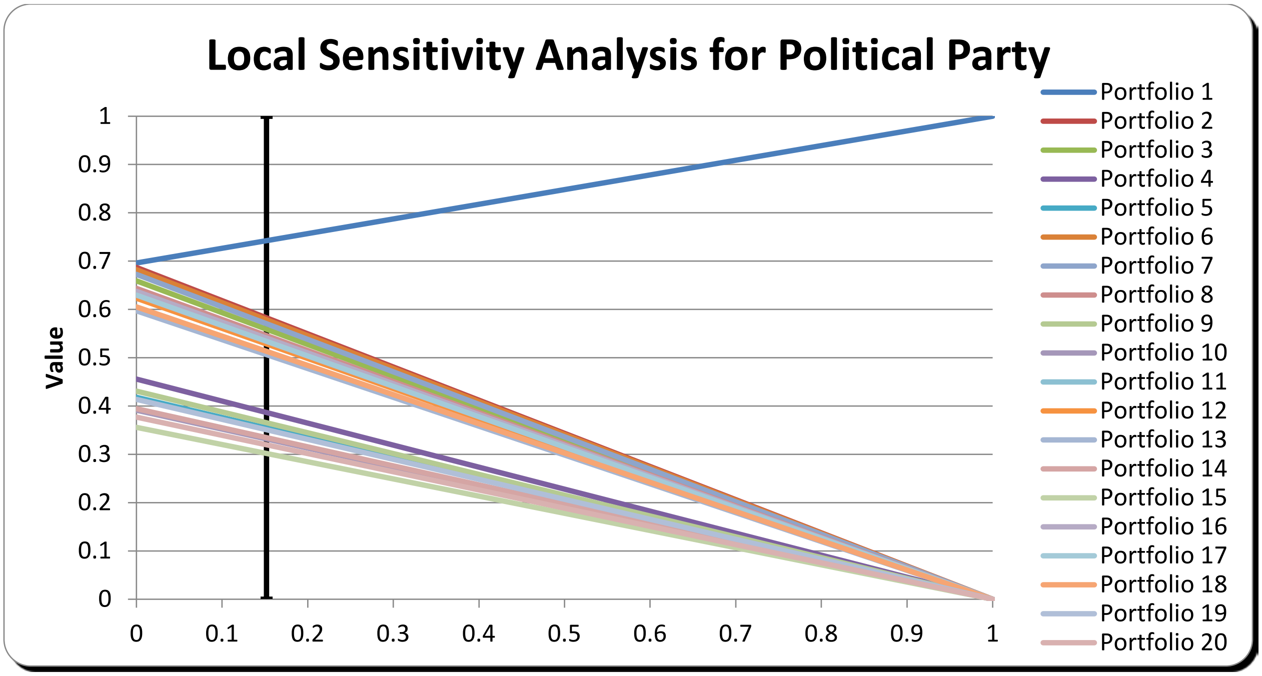
9. Silver Party DM # 9
    a. Local Sensitivity Graphs
        i. Constituent Satisfaction



        ii. Personal Ideology

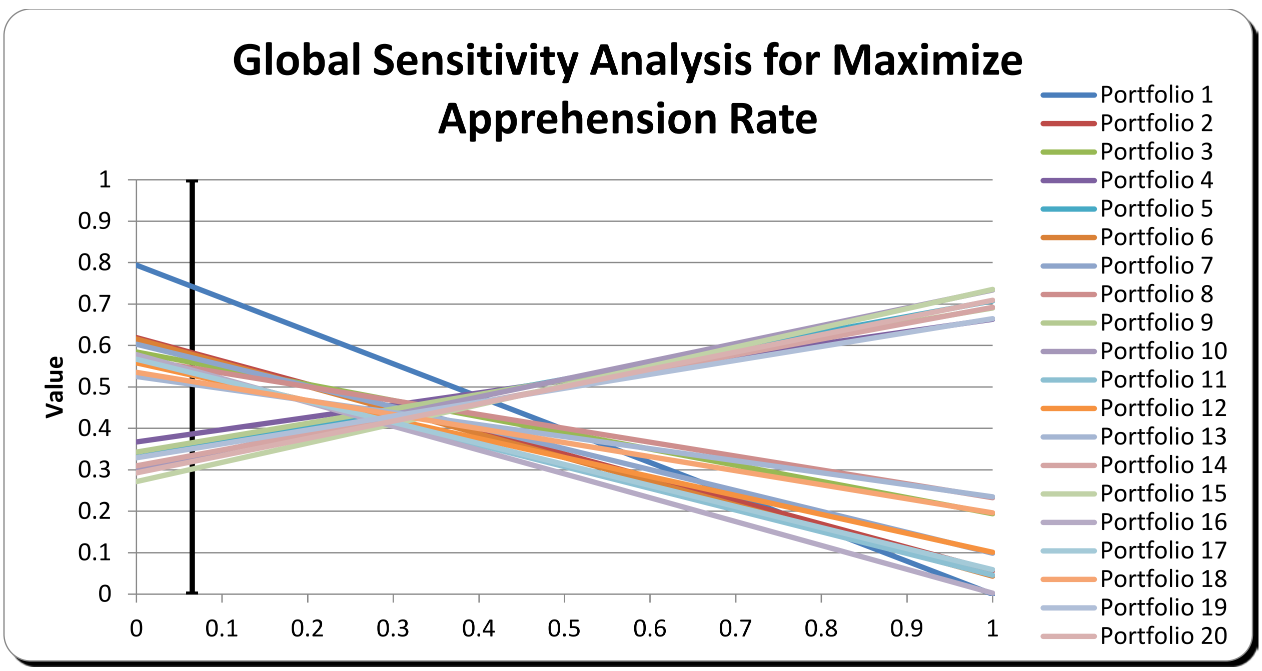


iii. Party Leader Support

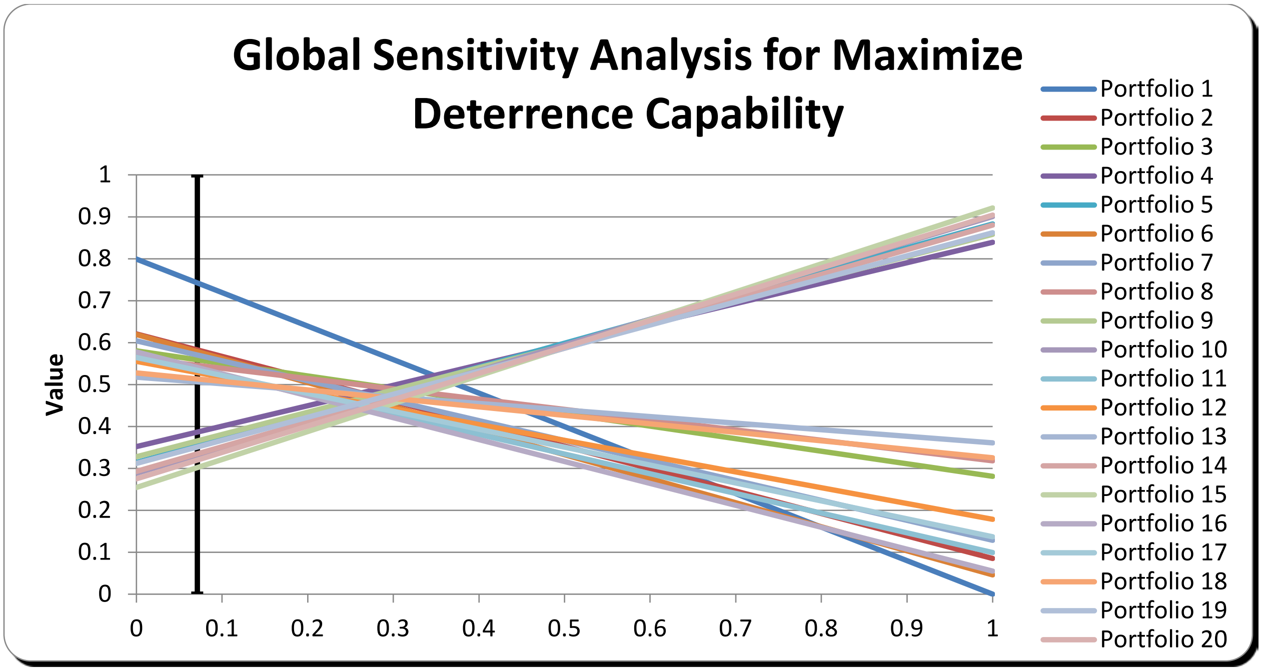


b. Global Sensitivity Graphs

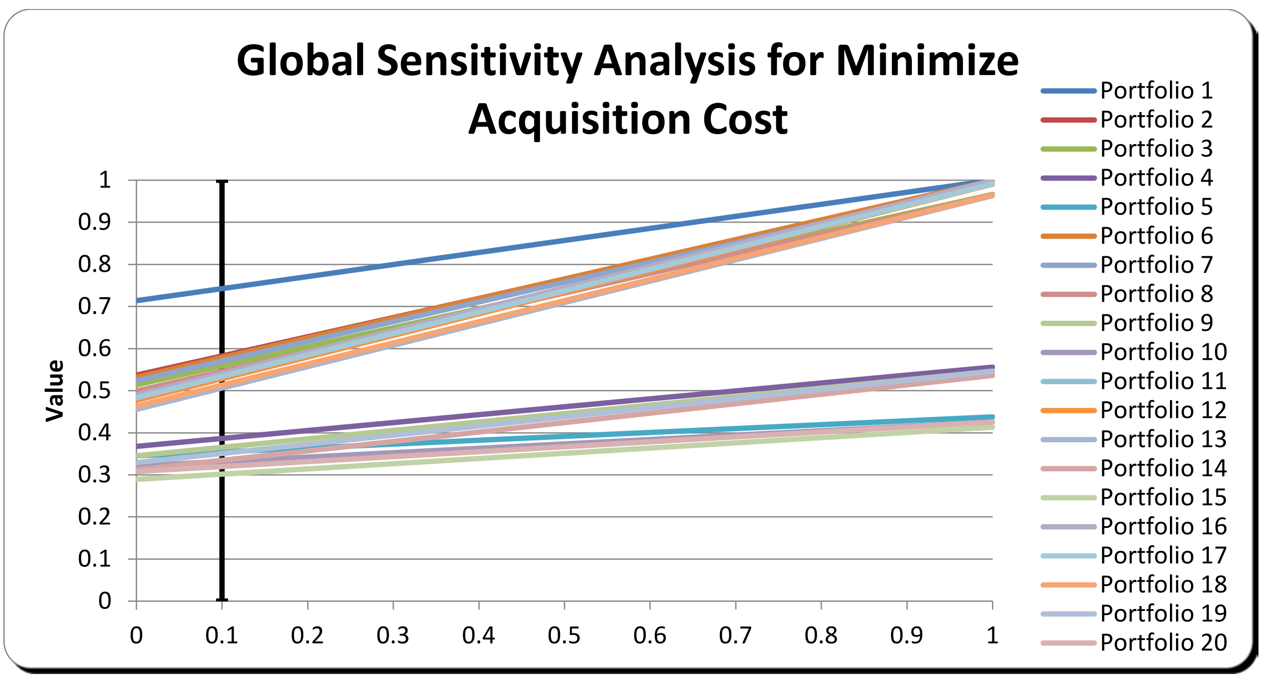
i. Maximize Apprehension Capability



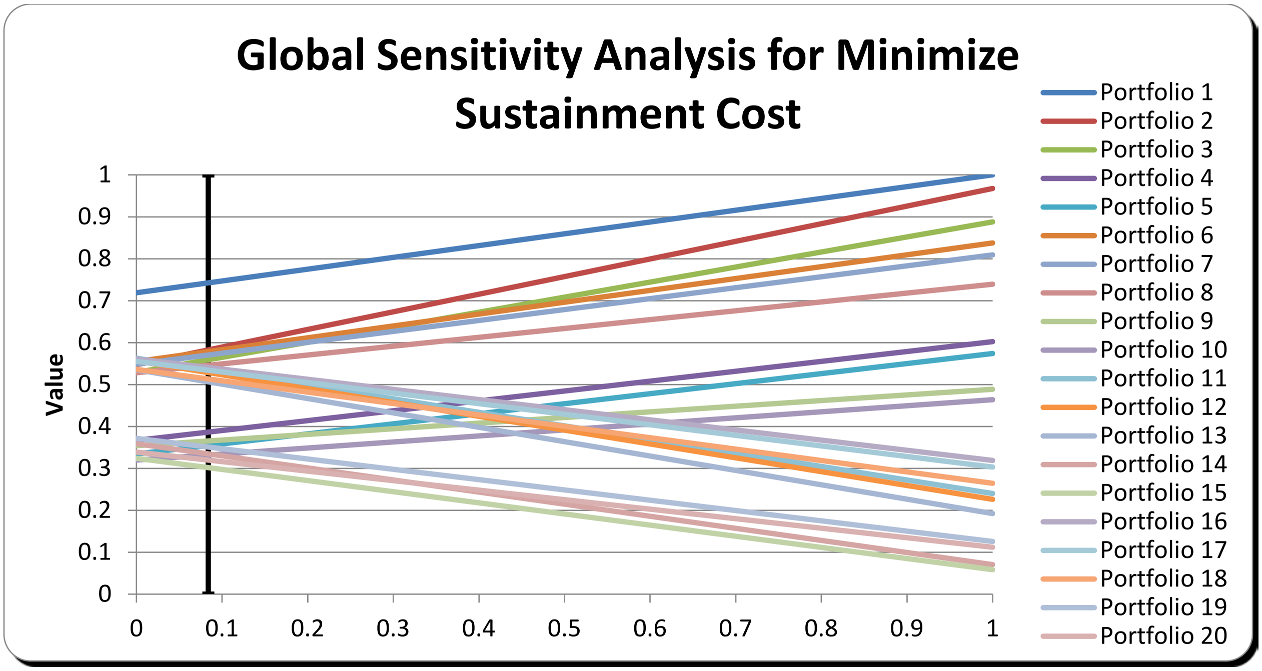
ii. Maximize Deterrence Capability



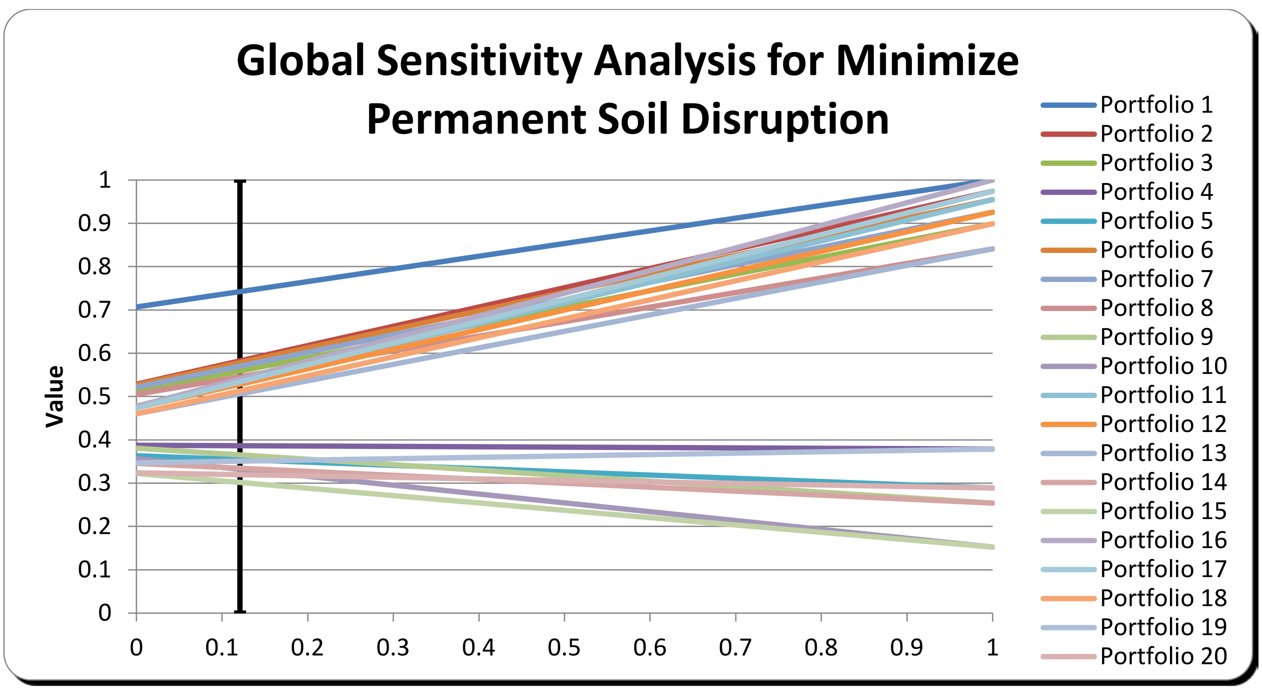
iii. Minimize Acquisition Cost



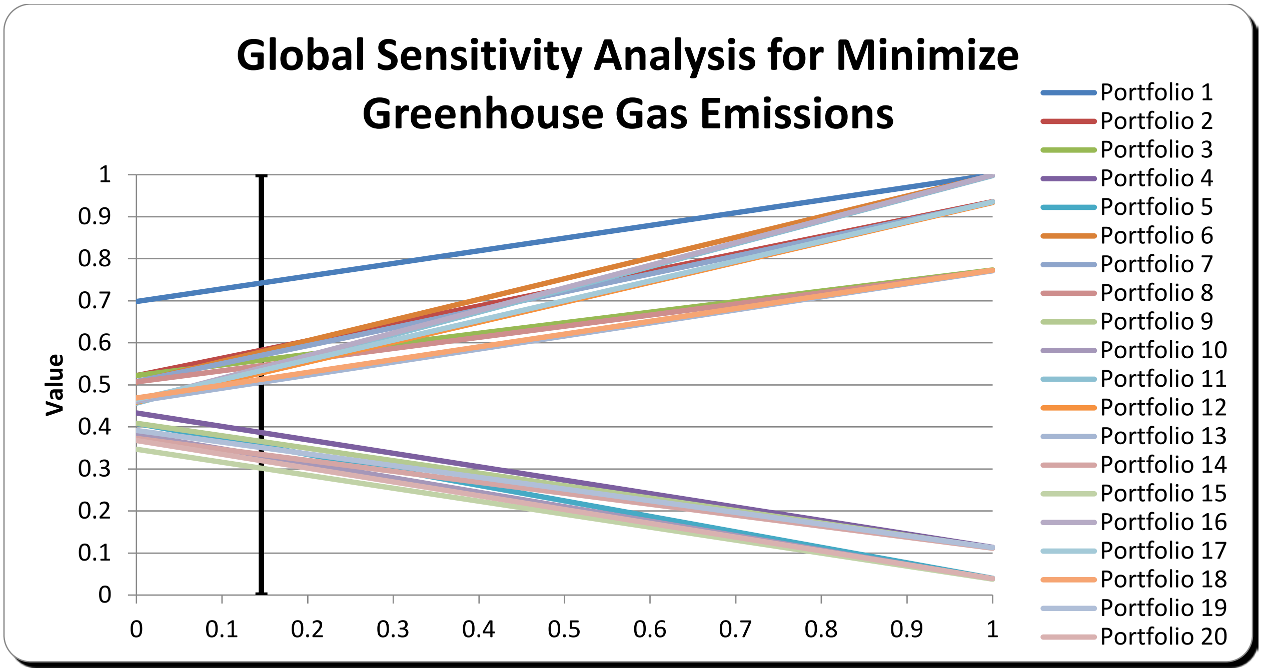
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



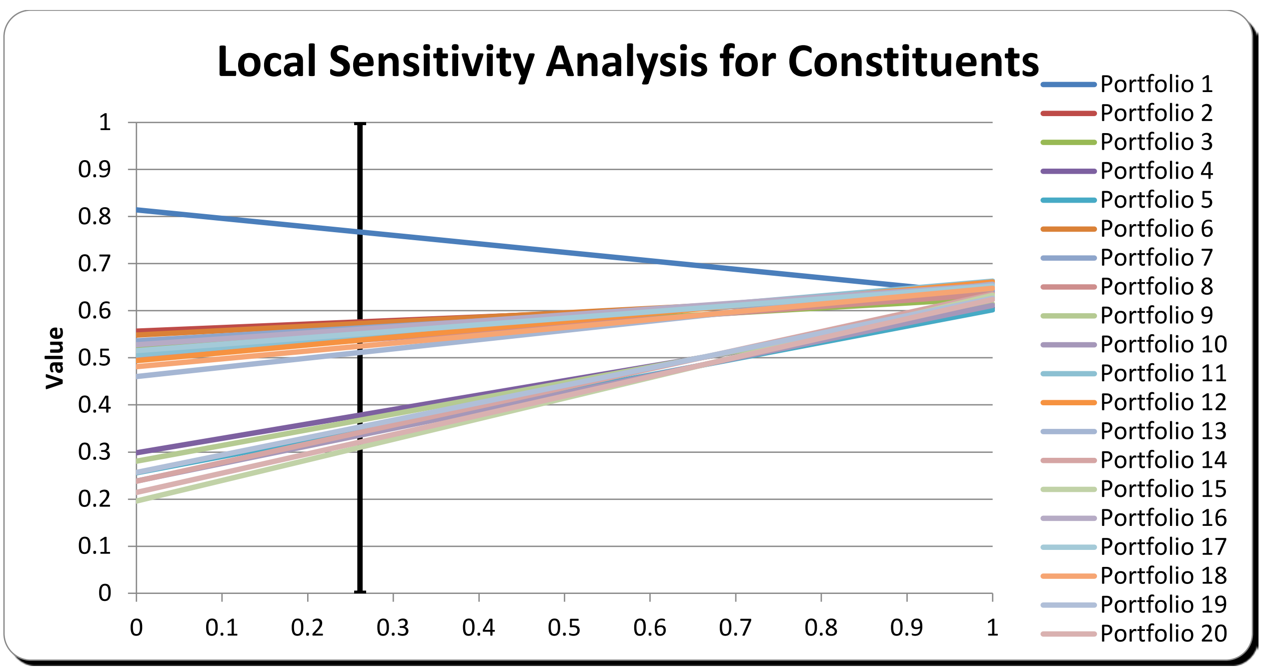
vi. Minimize Greenhouse Gas Emissions



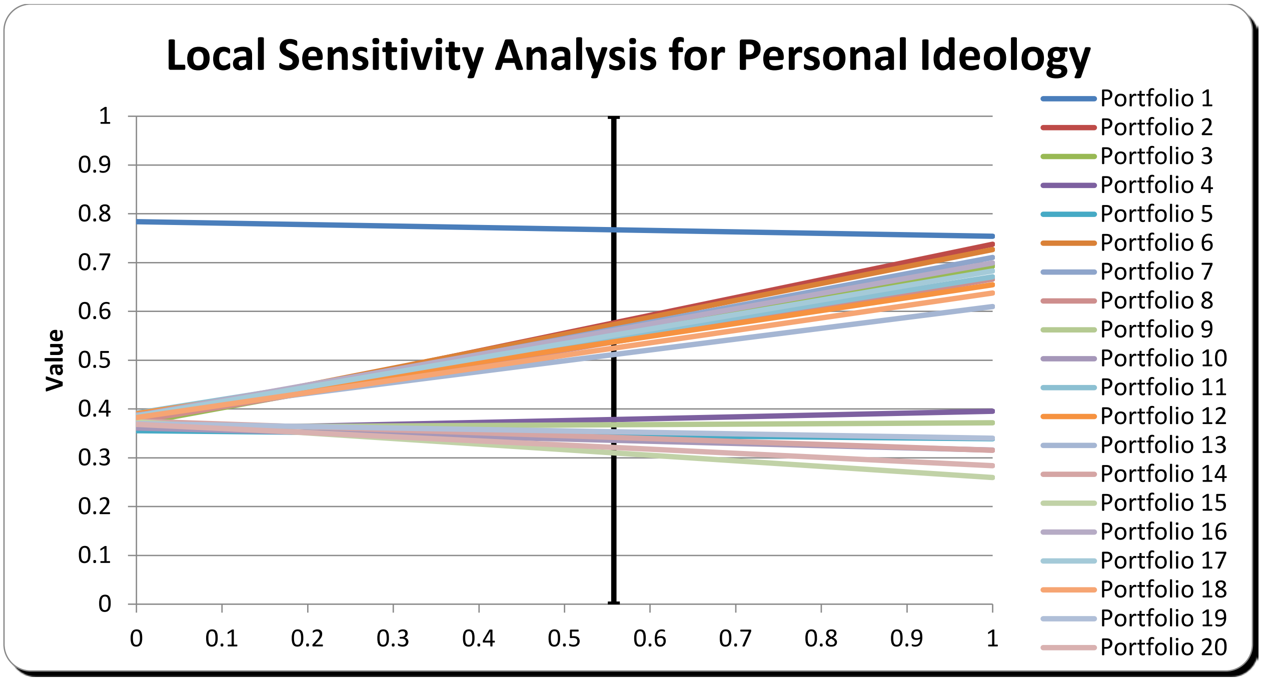
10. Silver Party DM # 10

a. Local Sensitivity Graphs

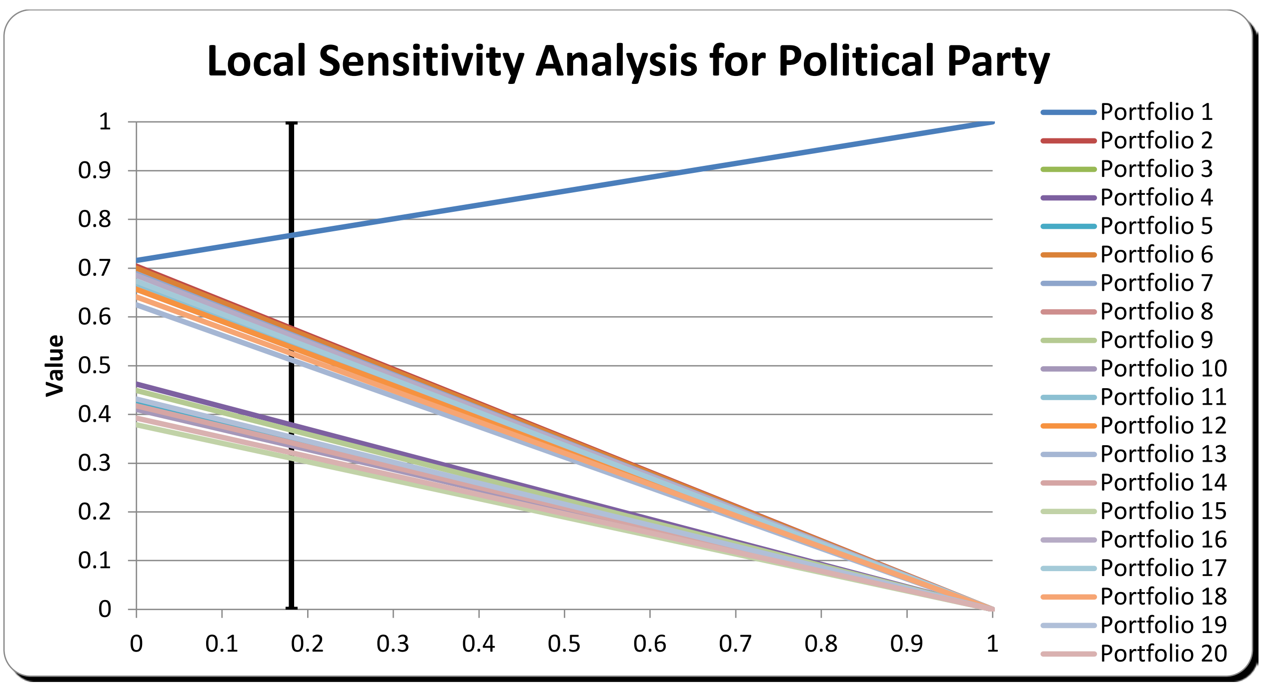
i. Constituent Satisfaction



ii. Personal Ideology

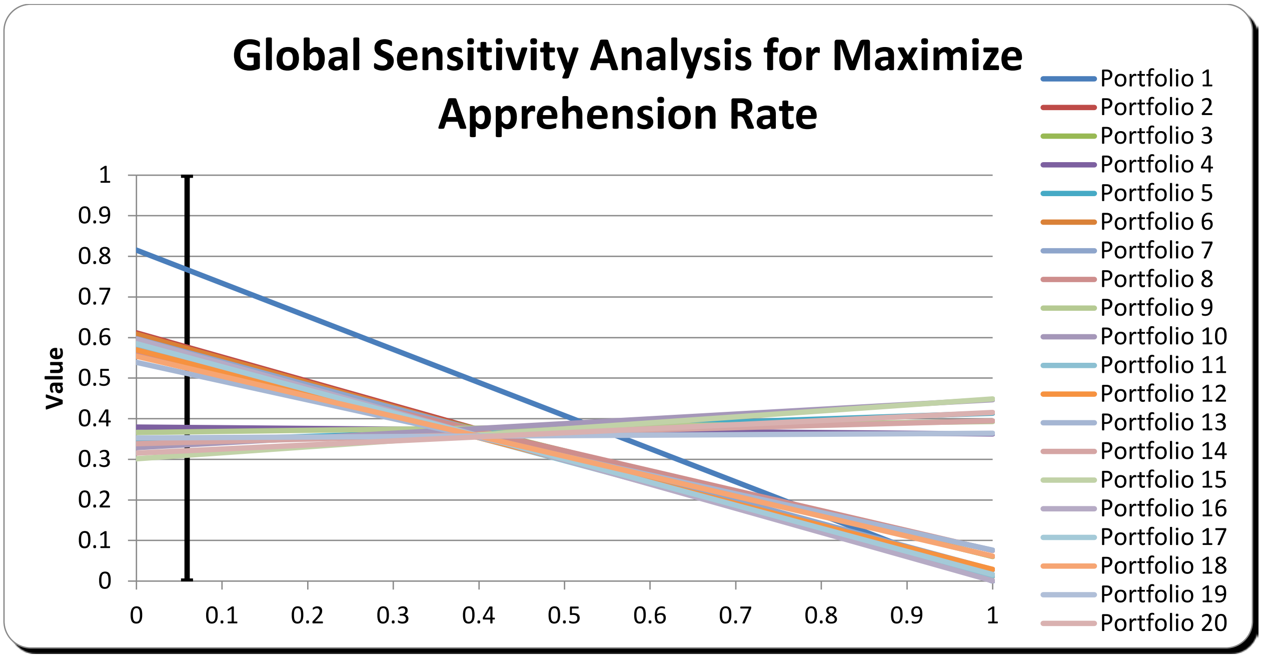


iii. Party Leader Support

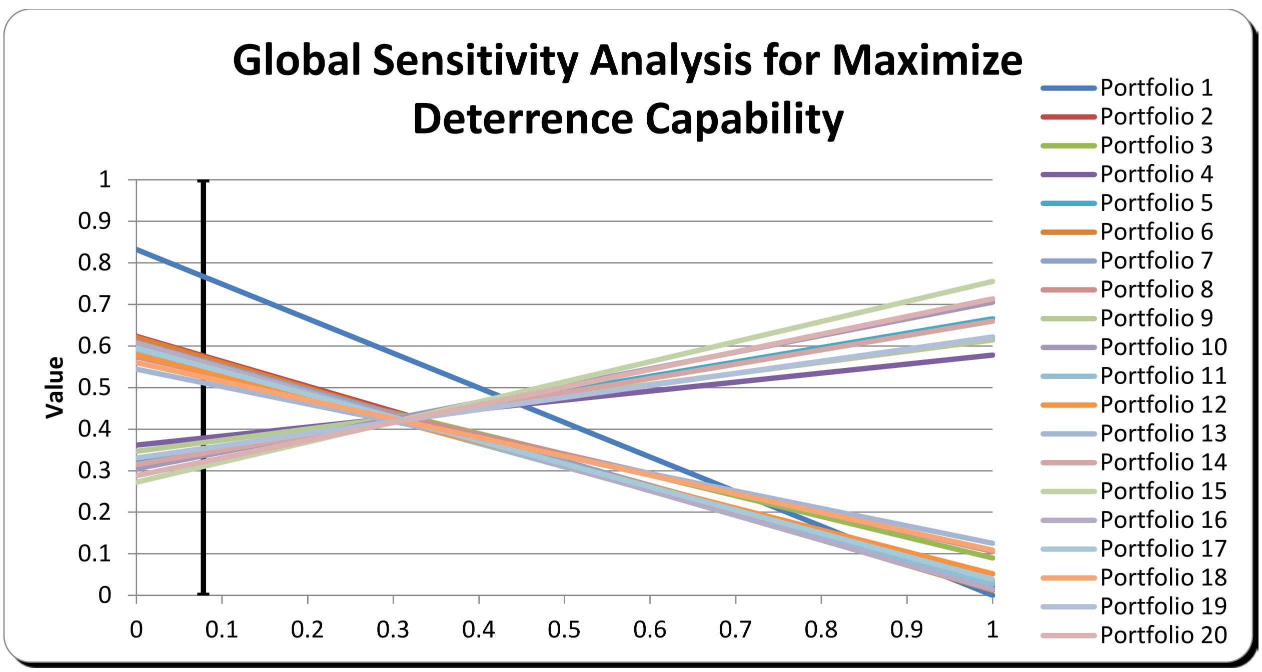


b. Global Sensitivity Graphs

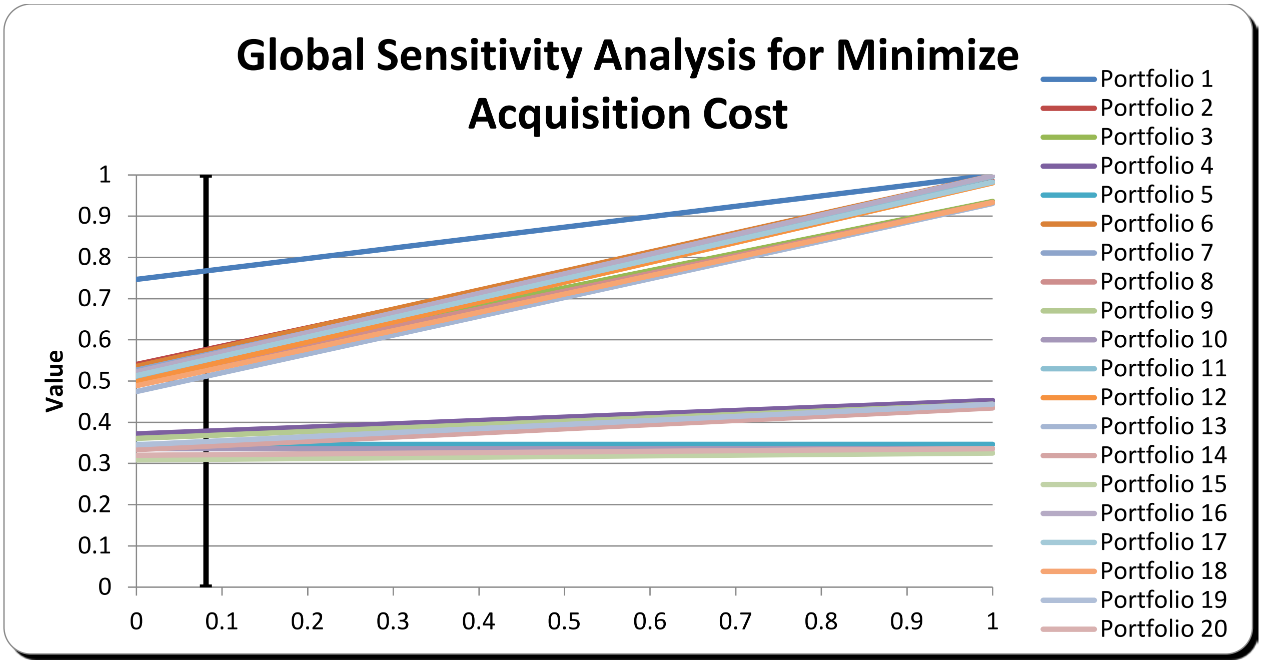
i. Maximize Apprehension Capability



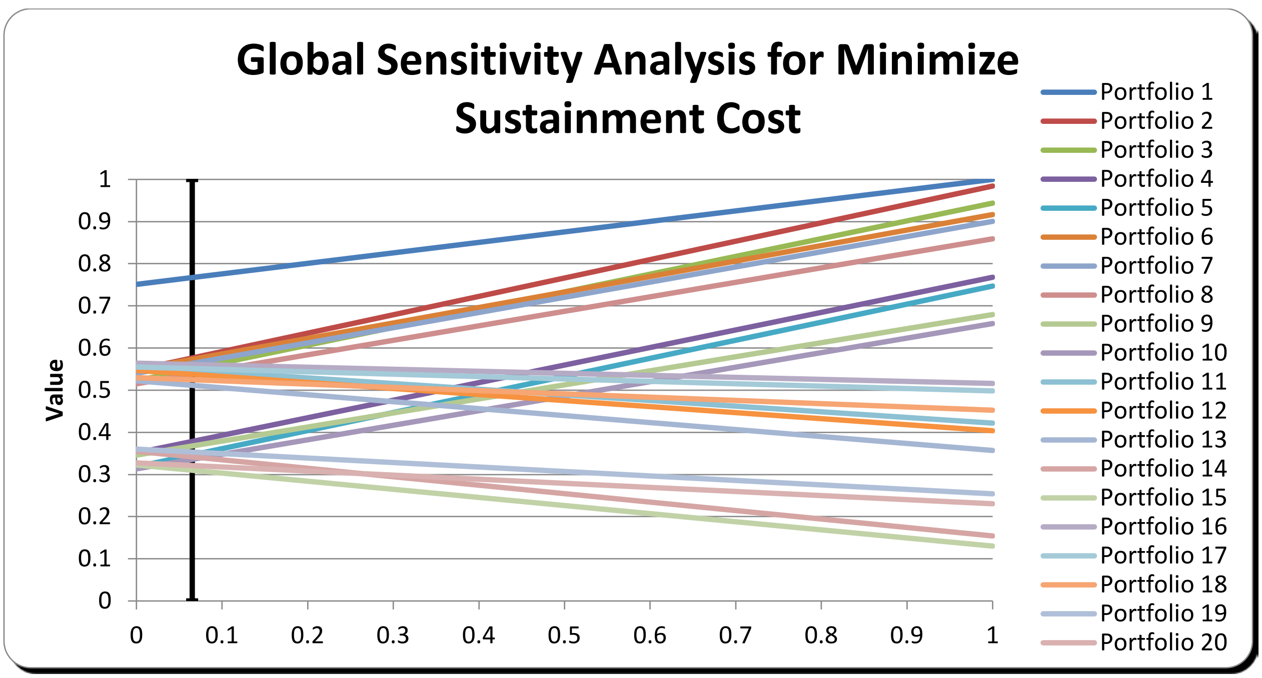
ii. Maximize Deterrence Capability



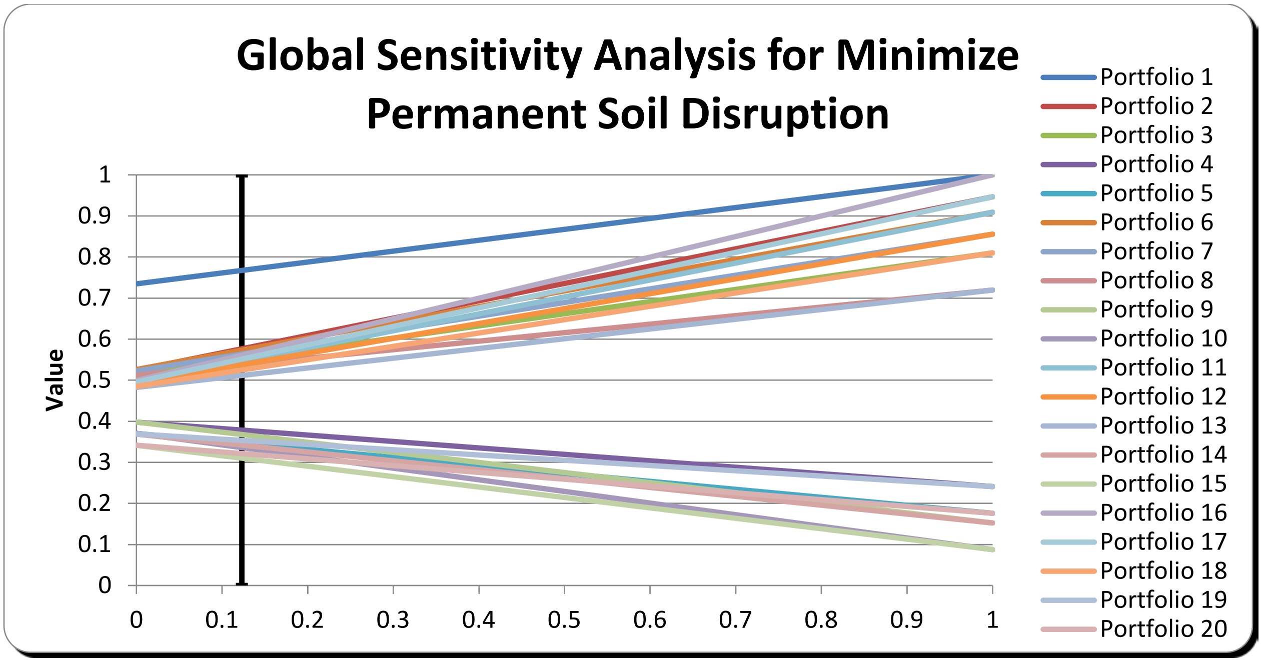
iii. Minimize Acquisition Cost



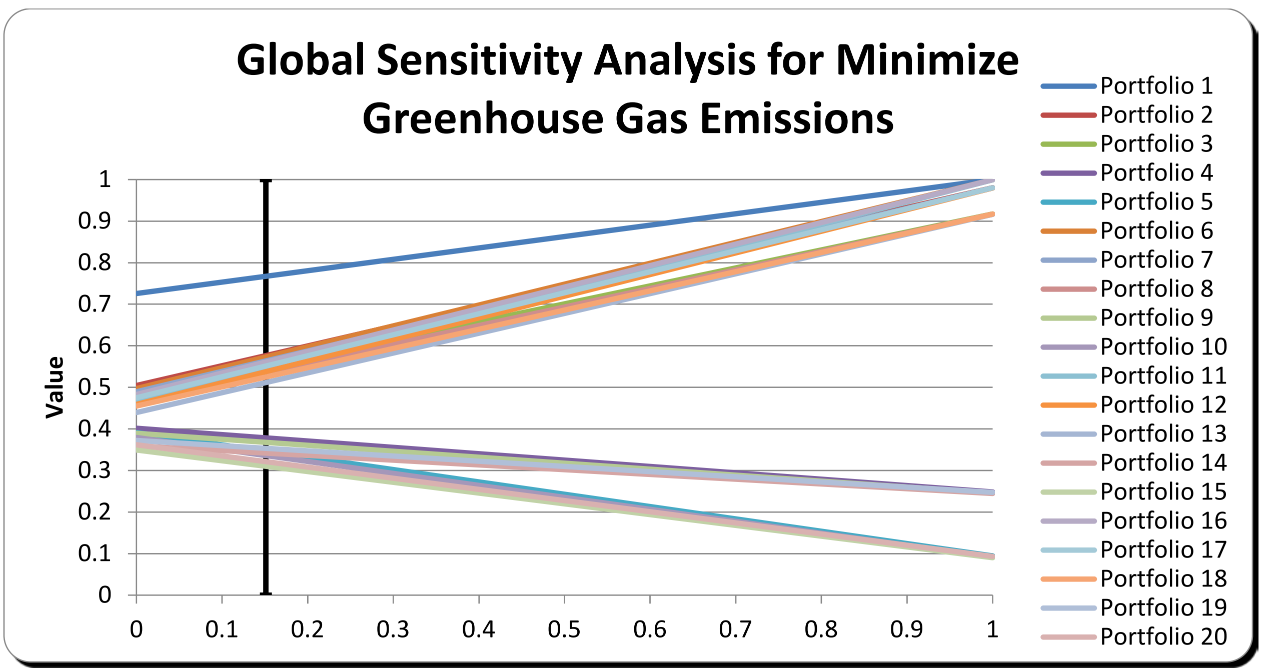
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



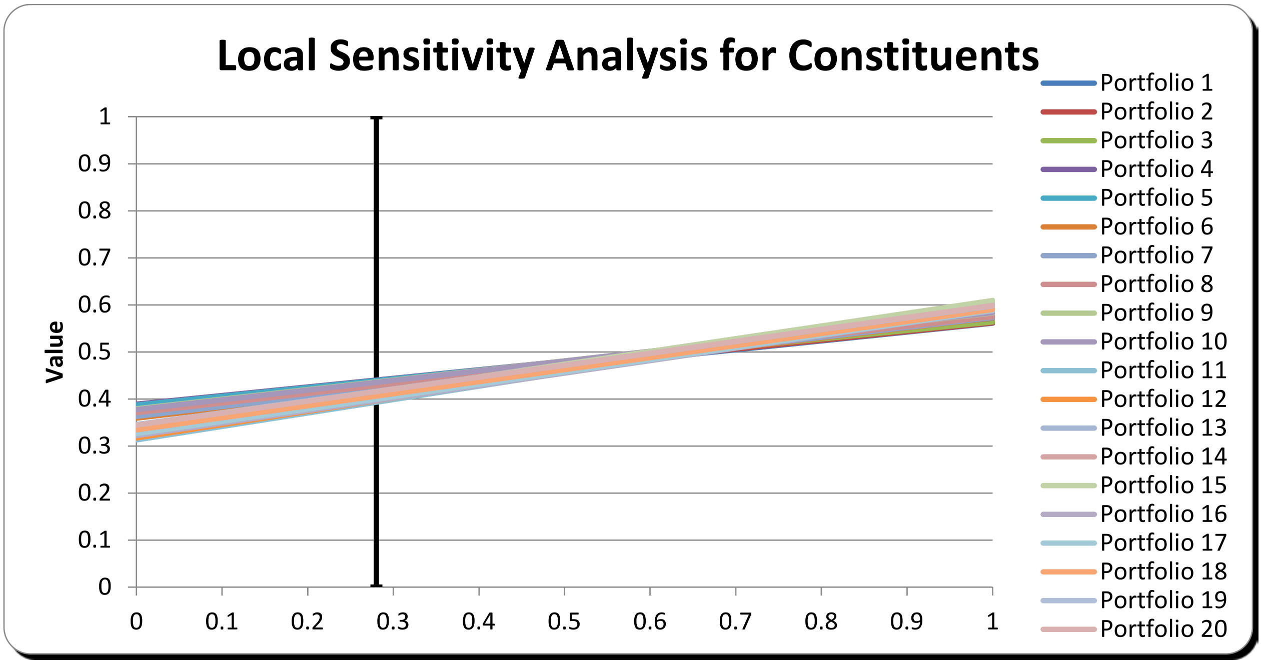
vi. Minimize Greenhouse Gas Emissions



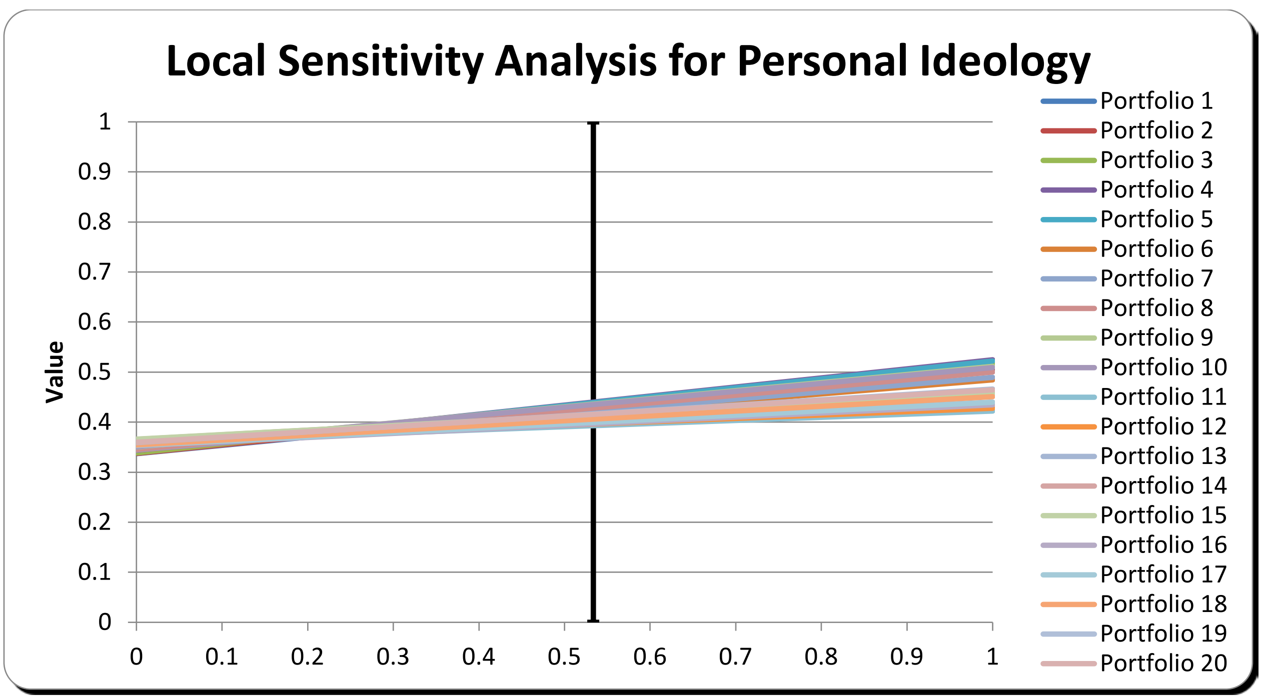
11. Gold Party Leader

a. Local Sensitivity Graphs

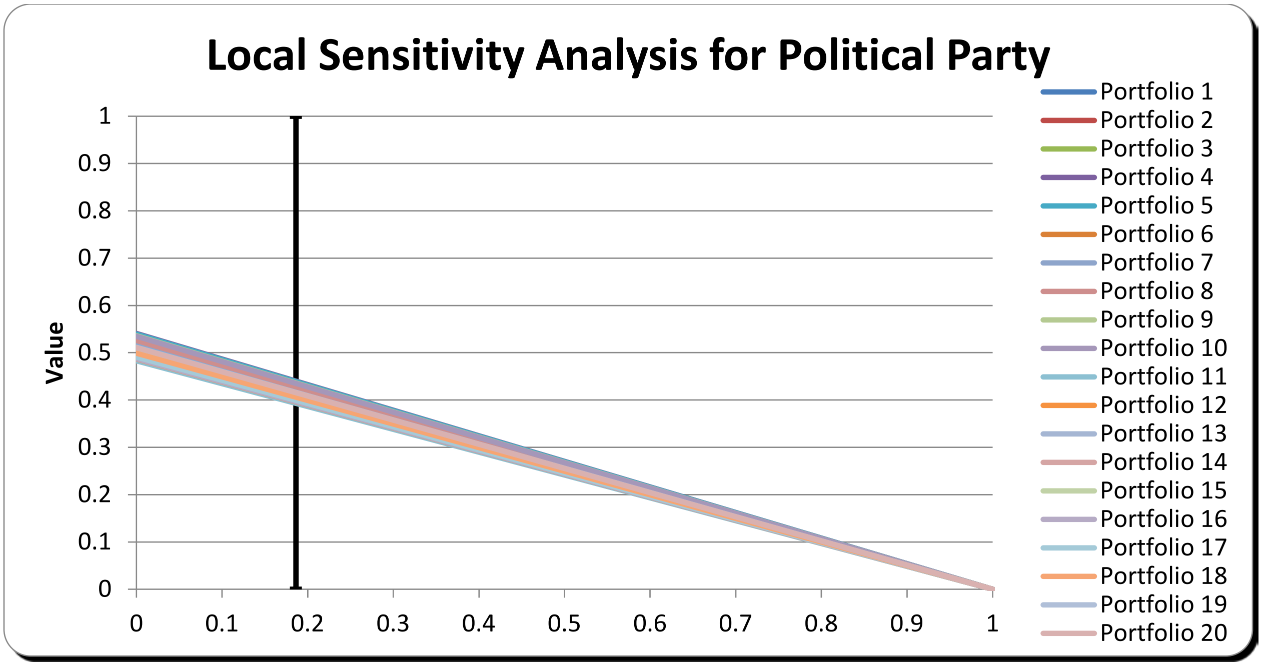
i. Constituent Satisfaction



ii. Personal Ideology

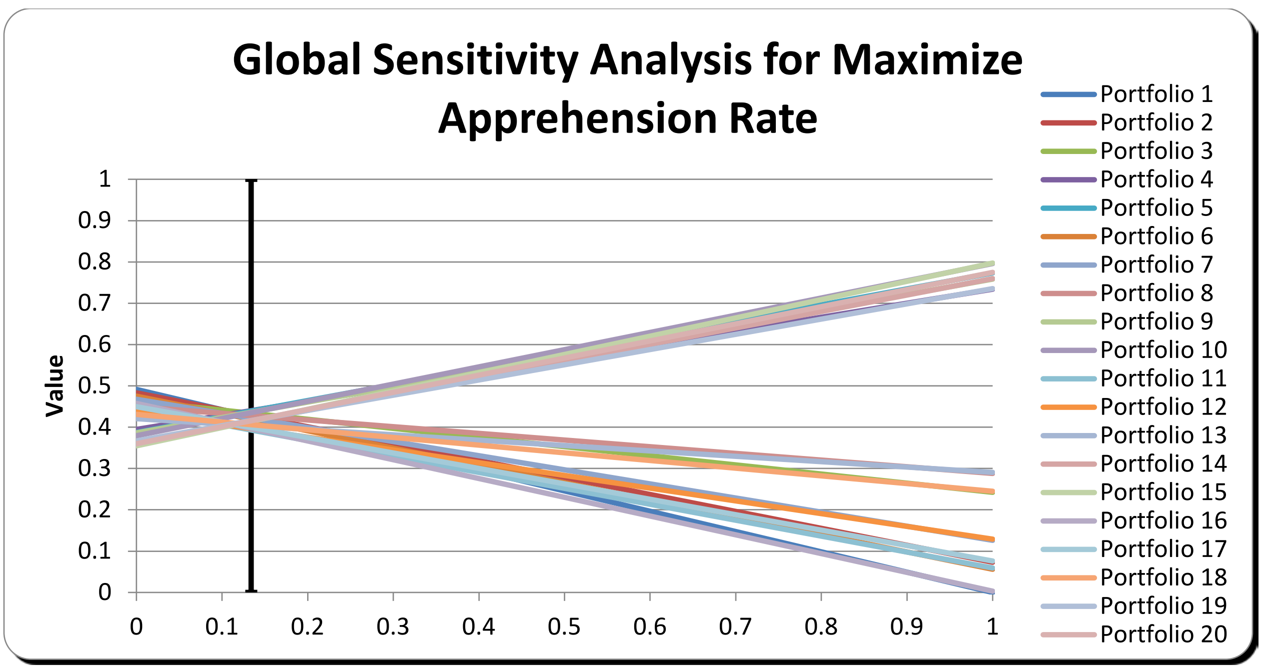


iii. Party Leader Support

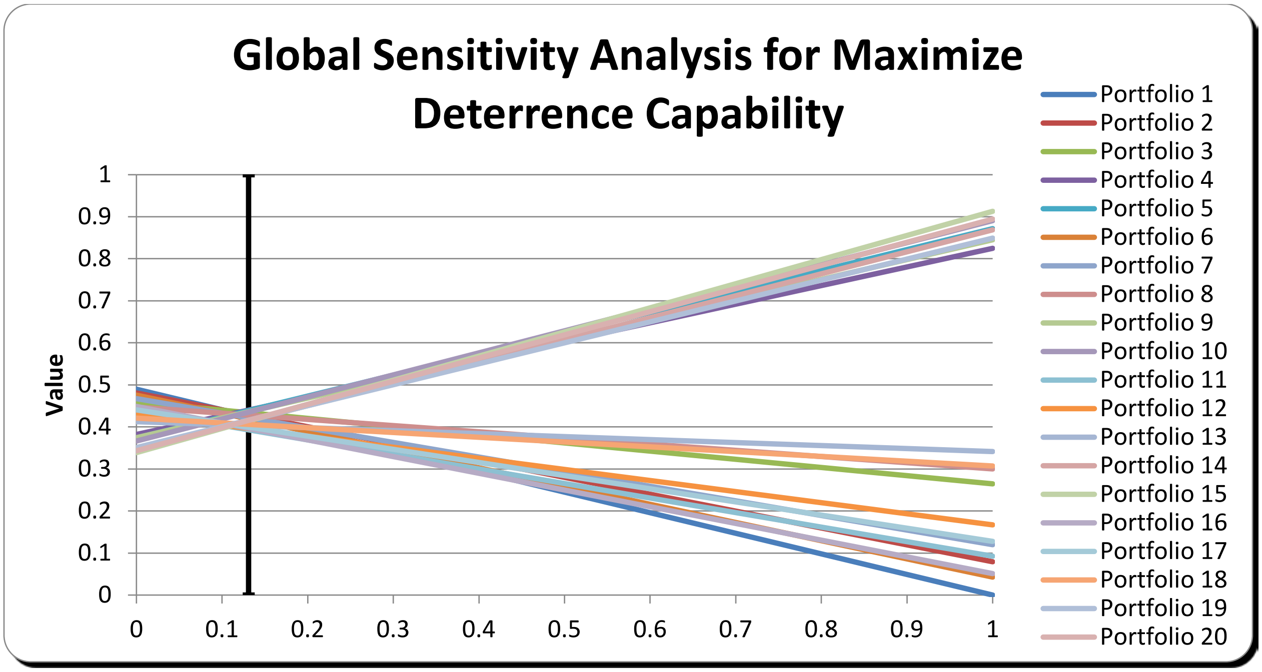


b. Global Sensitivity Graphs

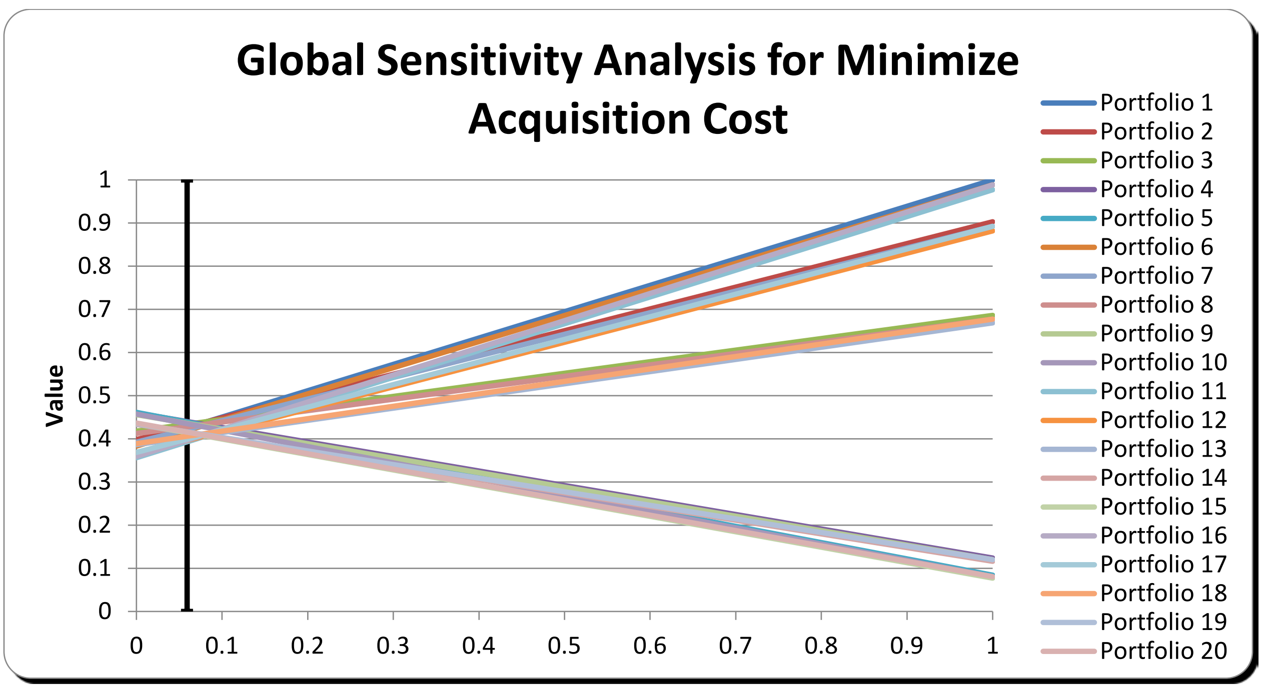
i. Maximize Apprehension Capability



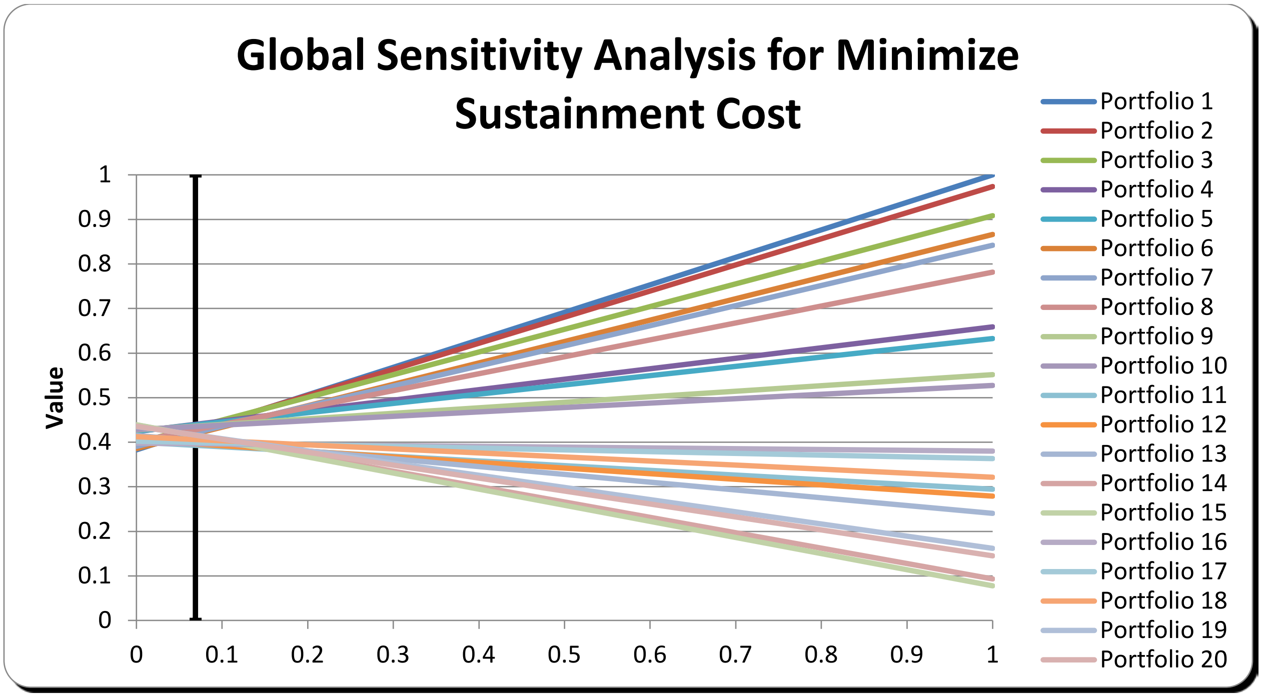
ii. Maximize Deterrence Capability



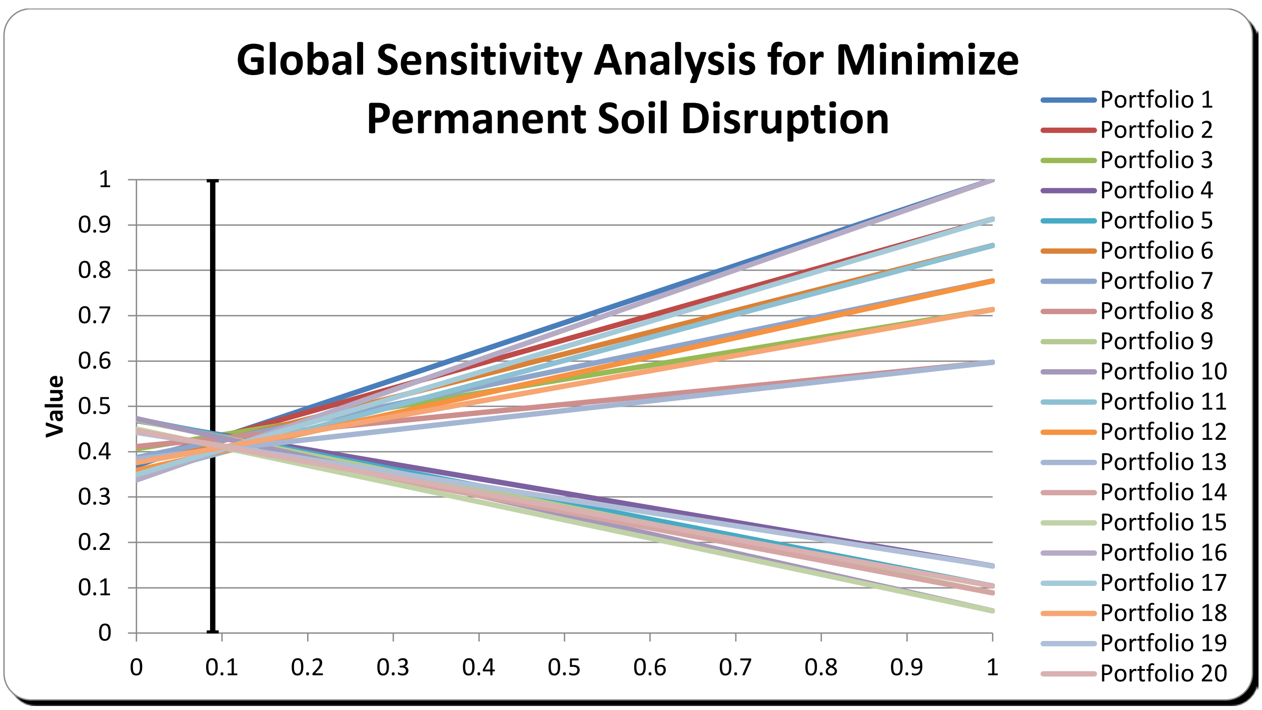
iii. Minimize Acquisition Cost



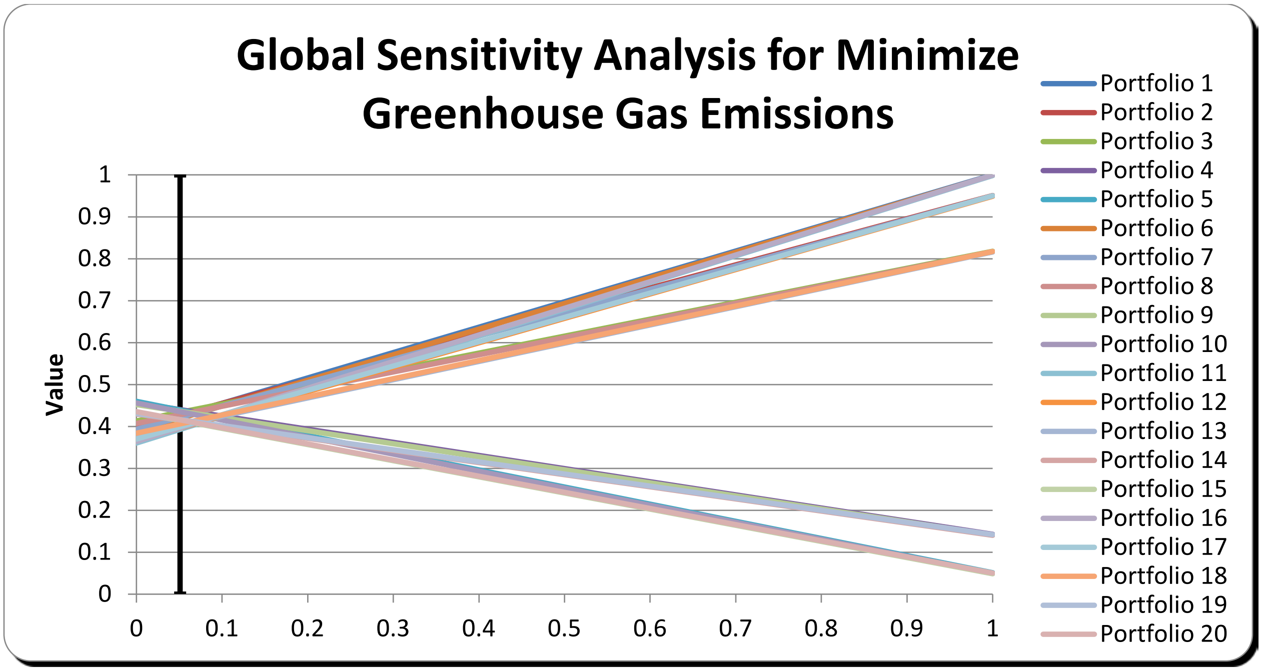
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



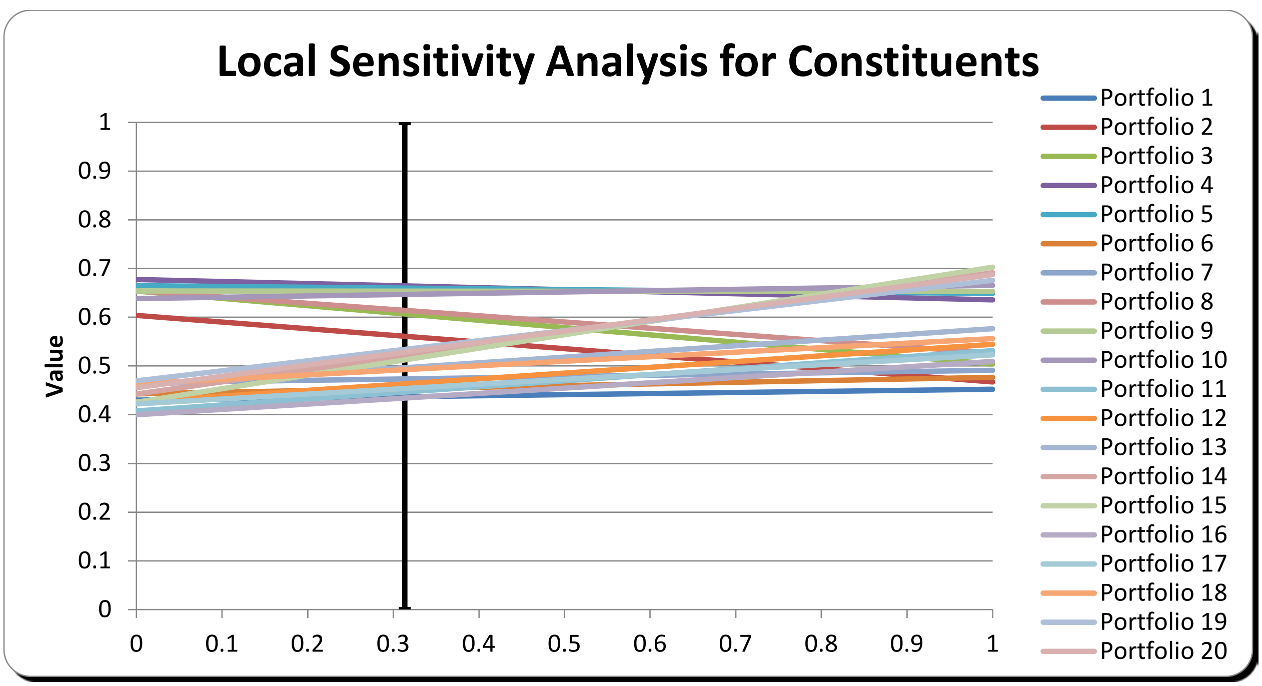
vi. Minimize Greenhouse Gas Emissions



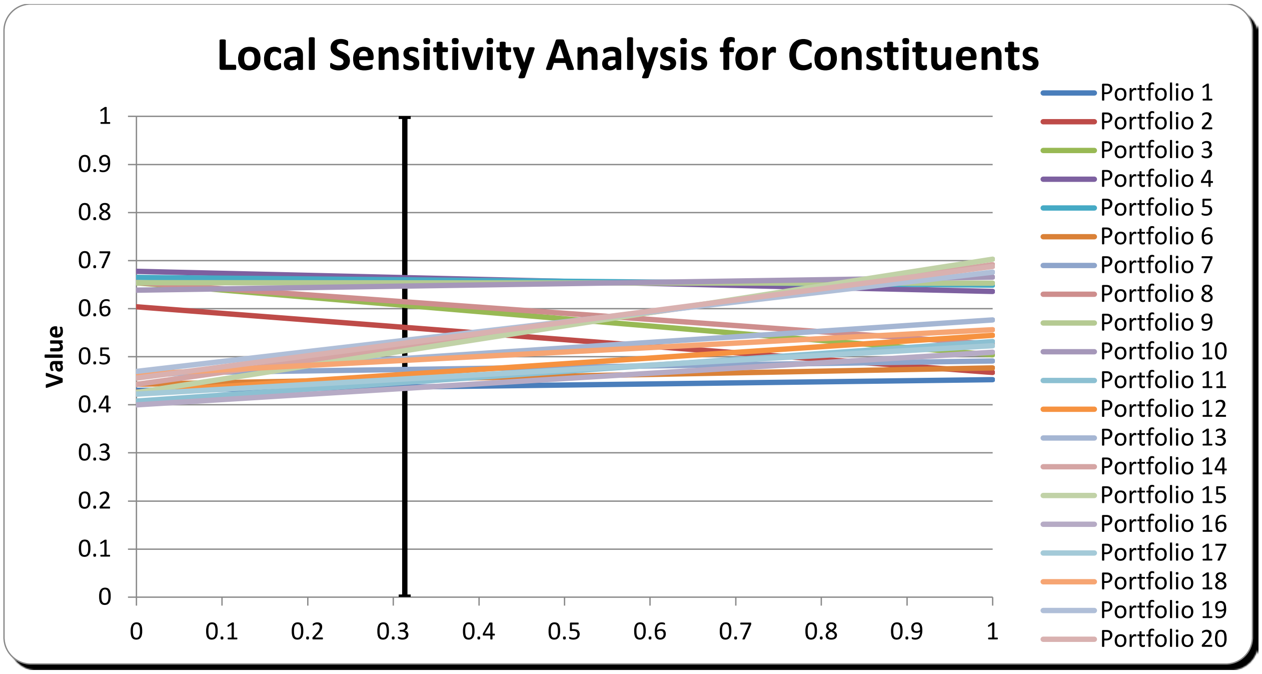
12. Gold Party DM # 2

a. Local Sensitivity Graphs

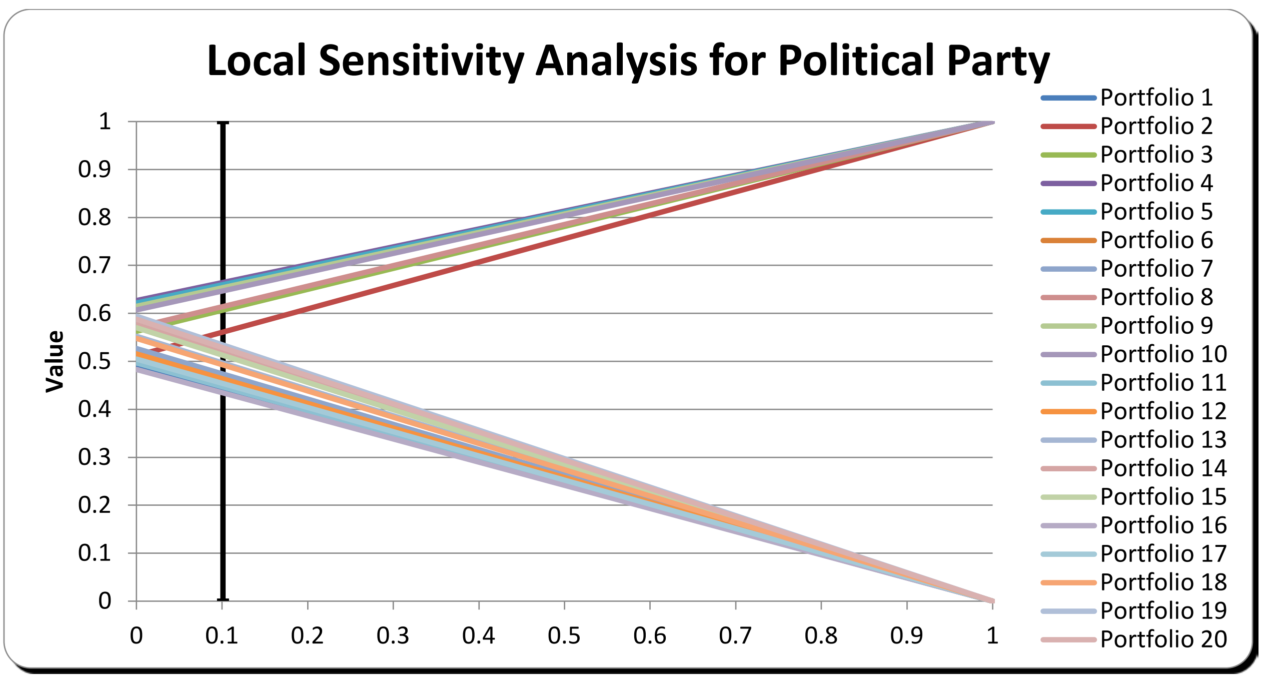
i. Constituent Satisfaction



ii. Personal Ideology

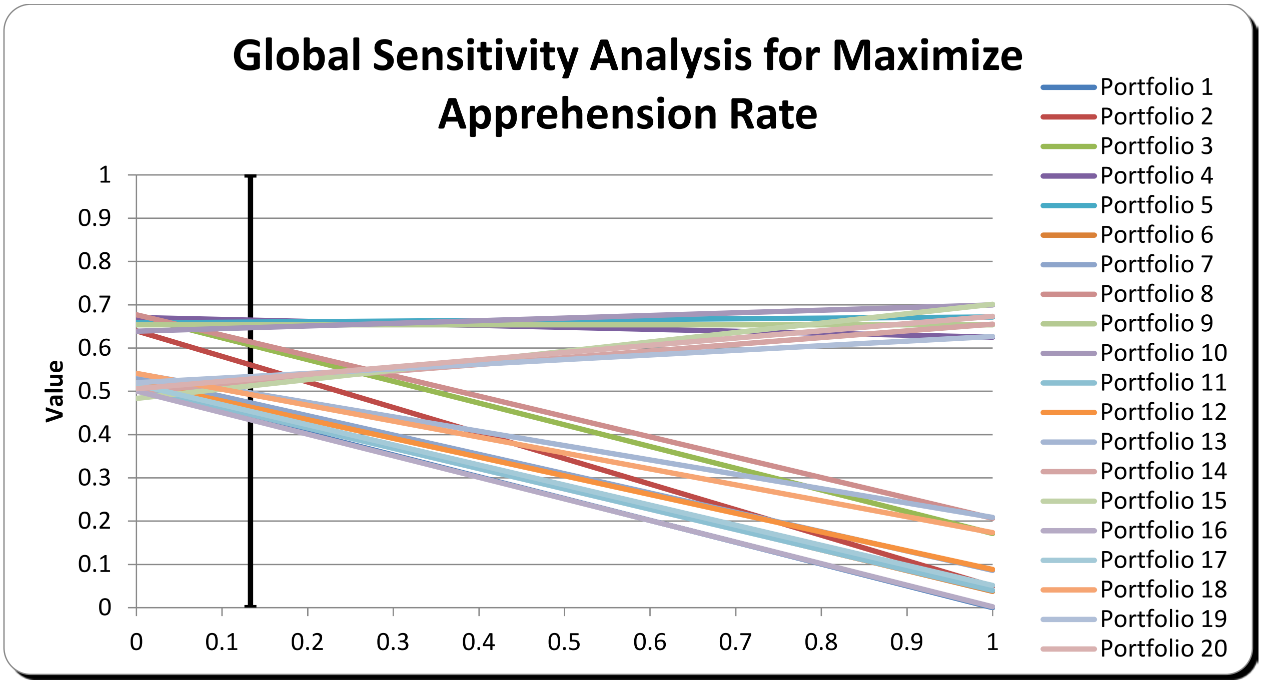


iii. Party Leader Support

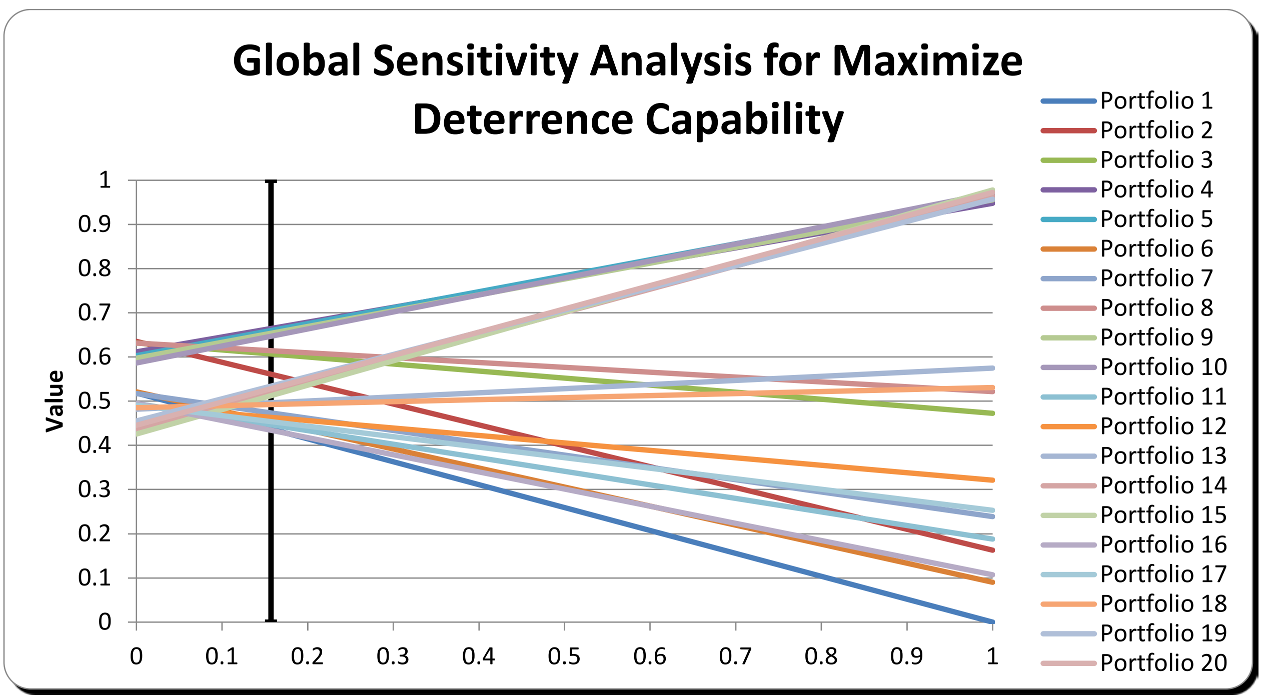


b. Global Sensitivity Graphs

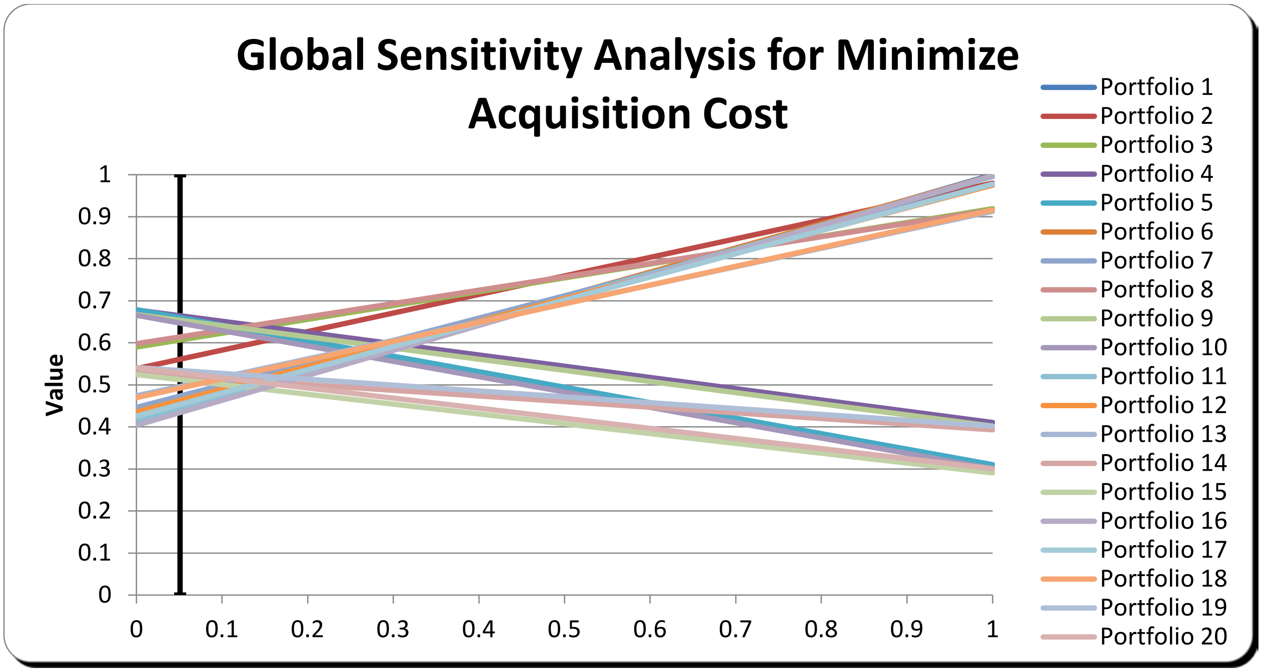
i. Maximize Apprehension Capability



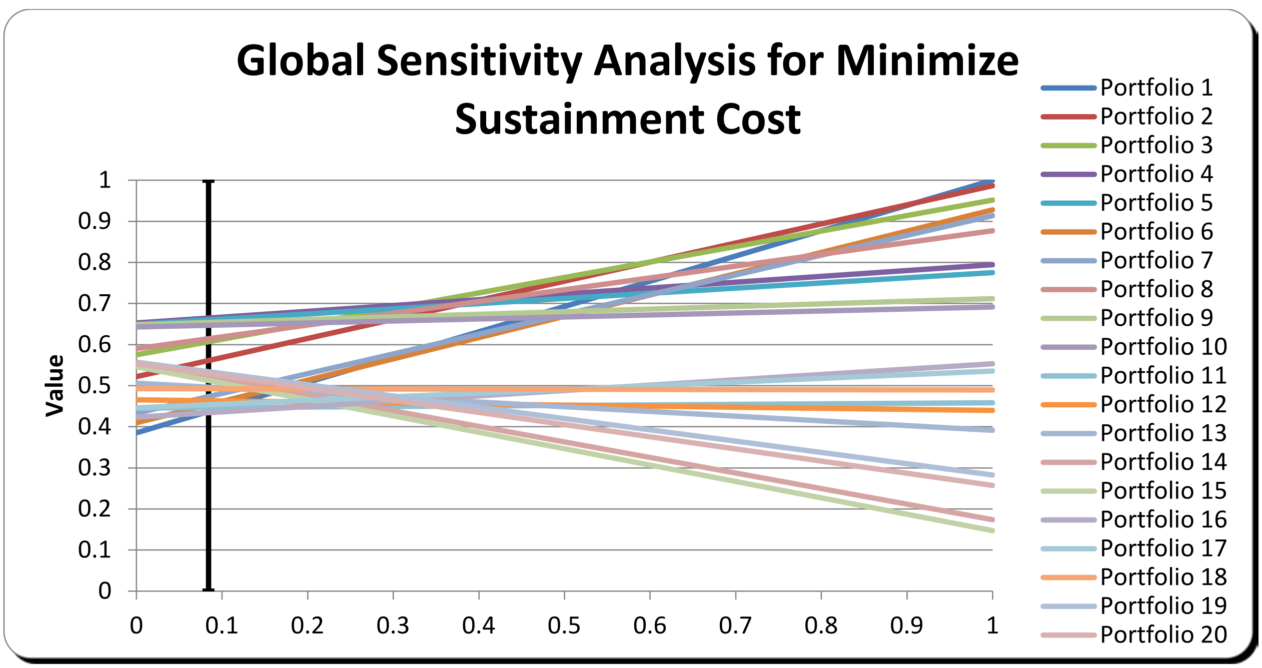
ii. Maximize Deterrence Capability



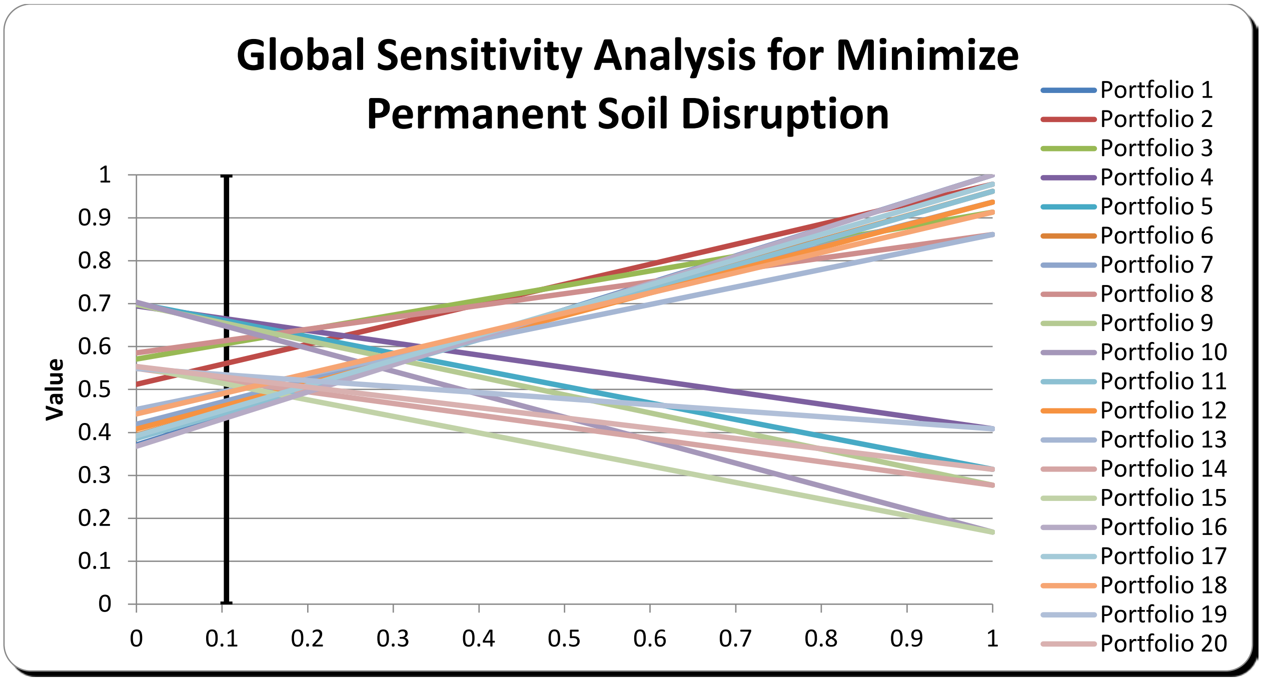
iii. Minimize Acquisition Cost



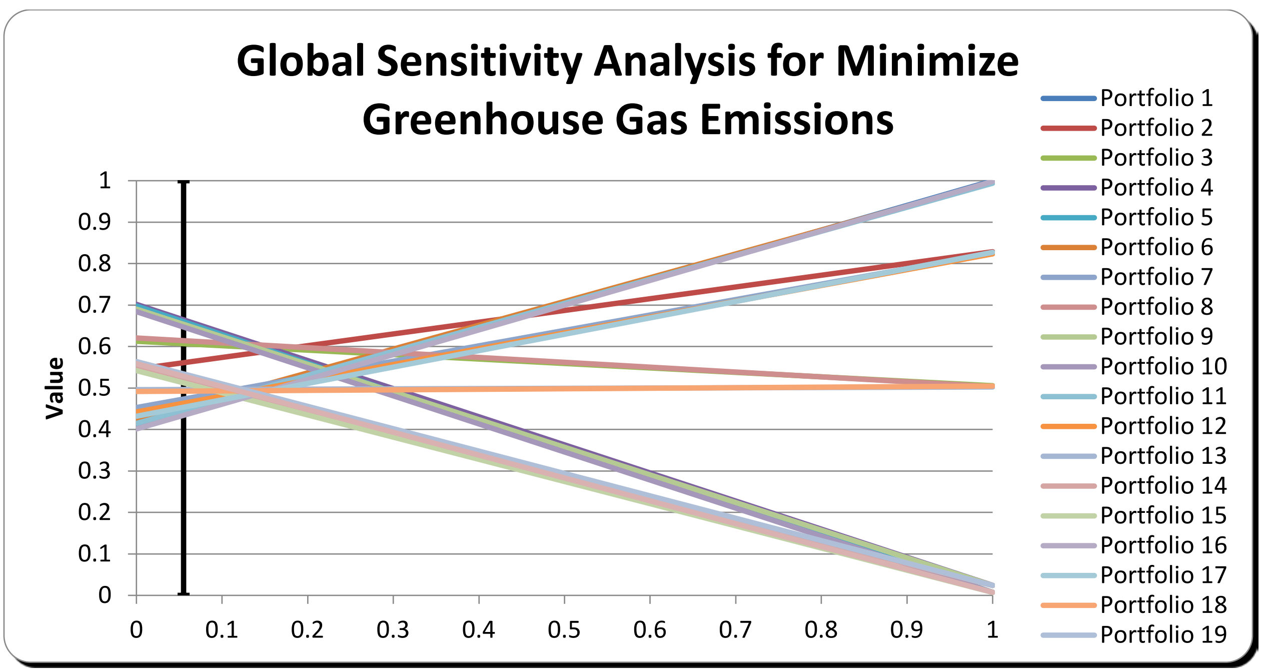
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



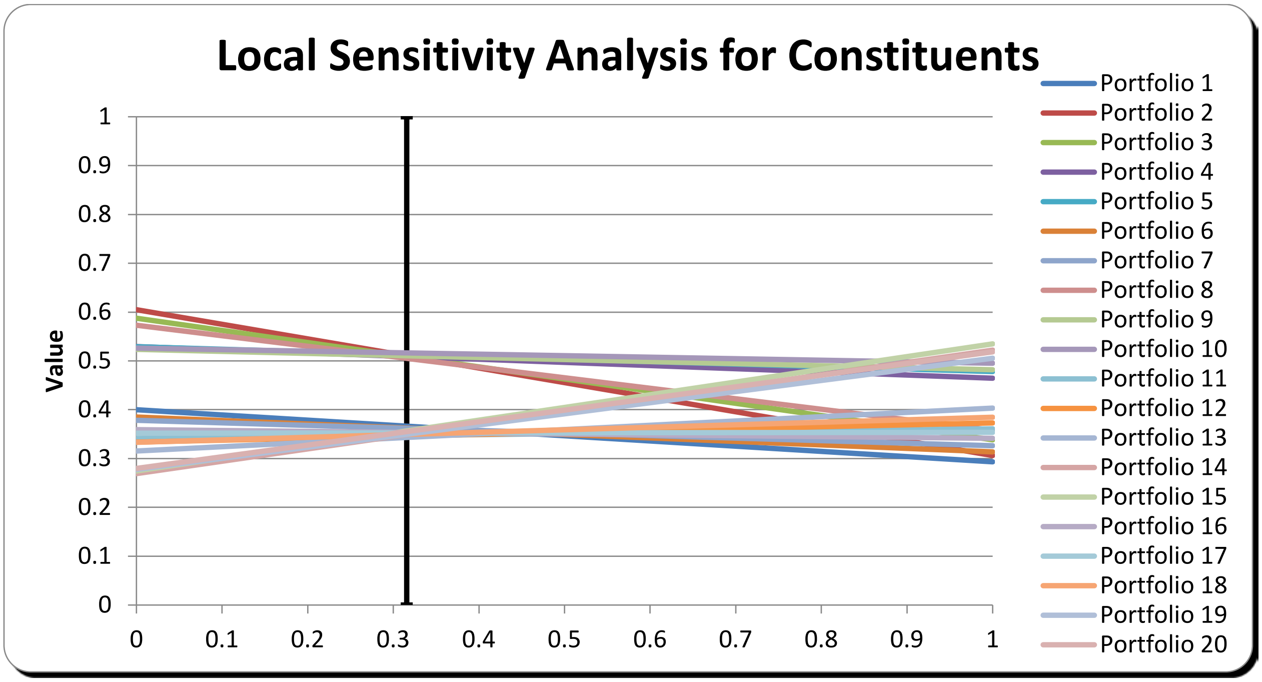
vi. Minimize Greenhouse Gas Emissions



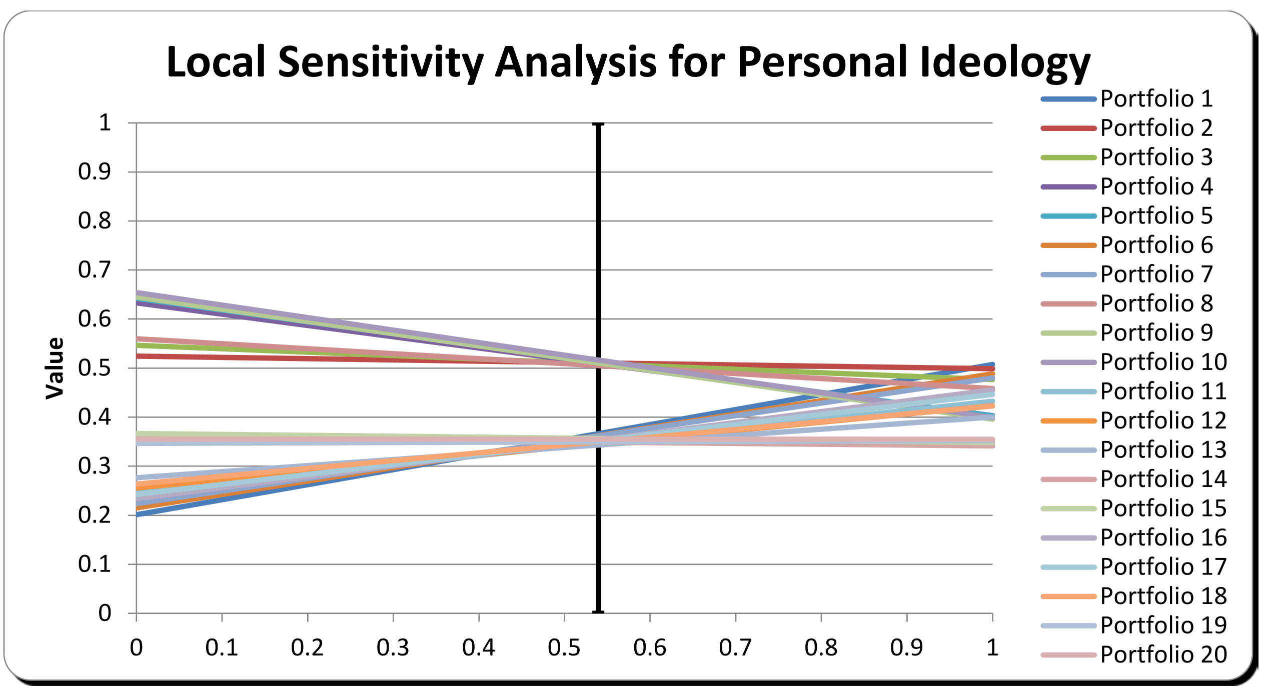
13. Gold Party DM # 3

a. Local Sensitivity Graphs

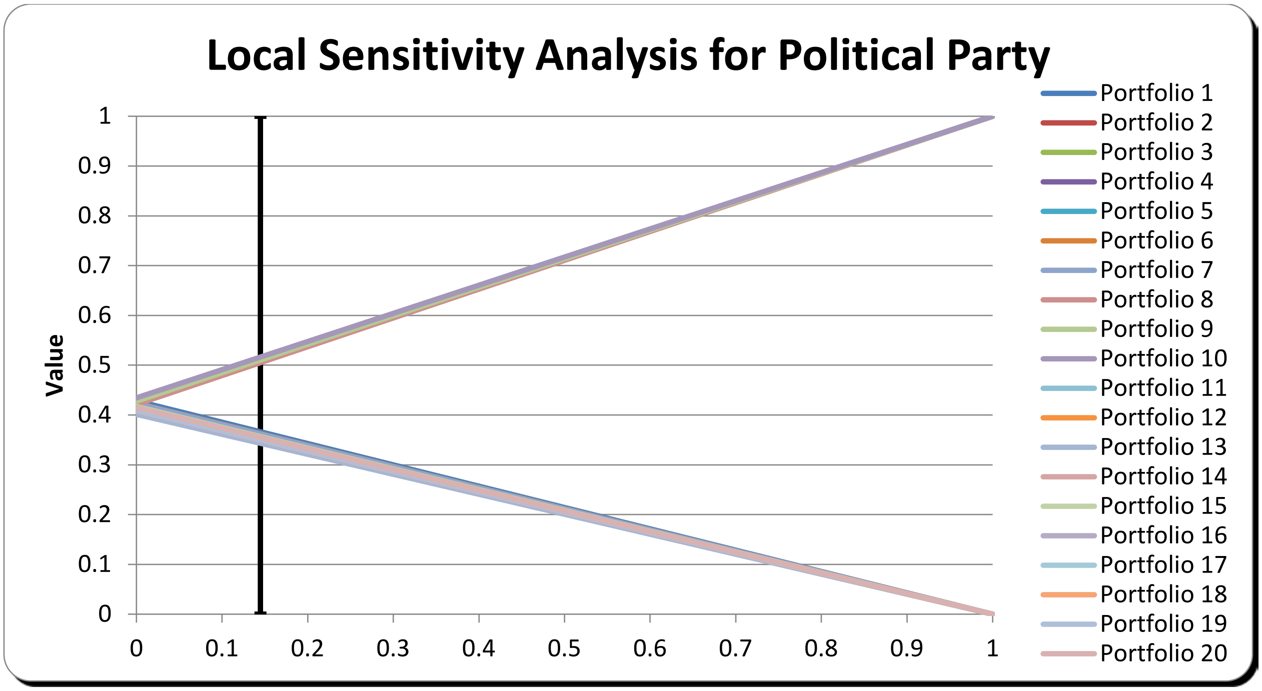
i. Constituent Satisfaction



ii. Personal Ideology

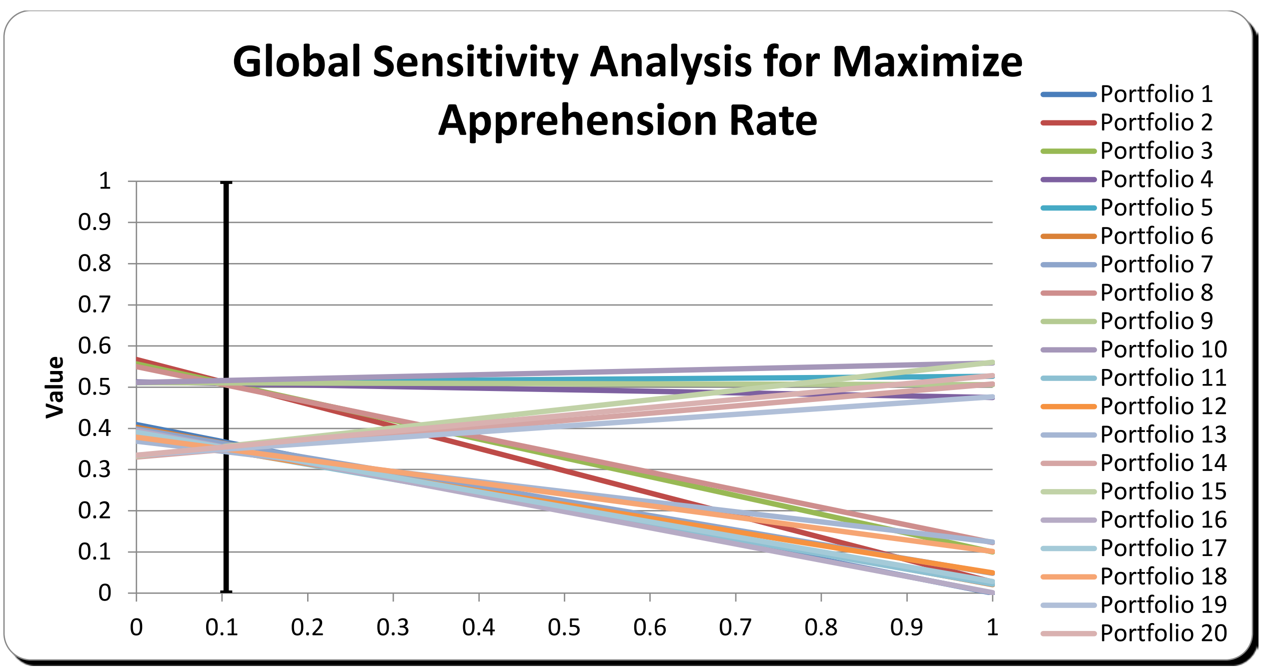


iii. Party Leader Support

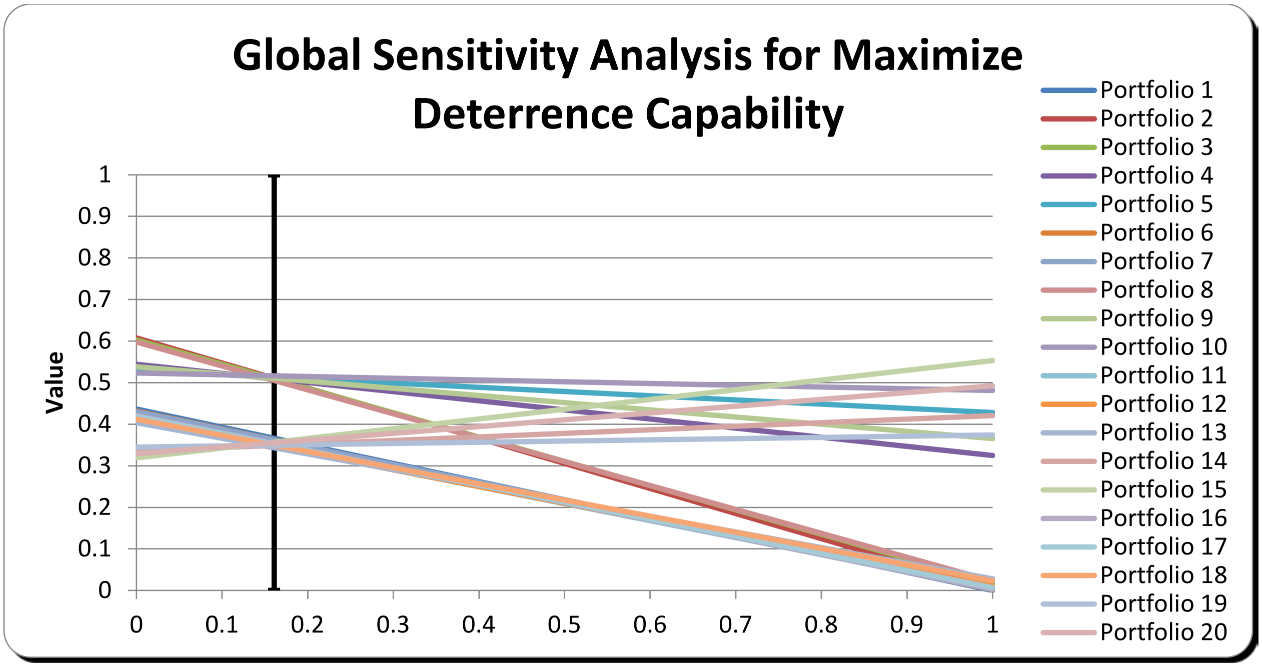


b. Global Sensitivity Graphs

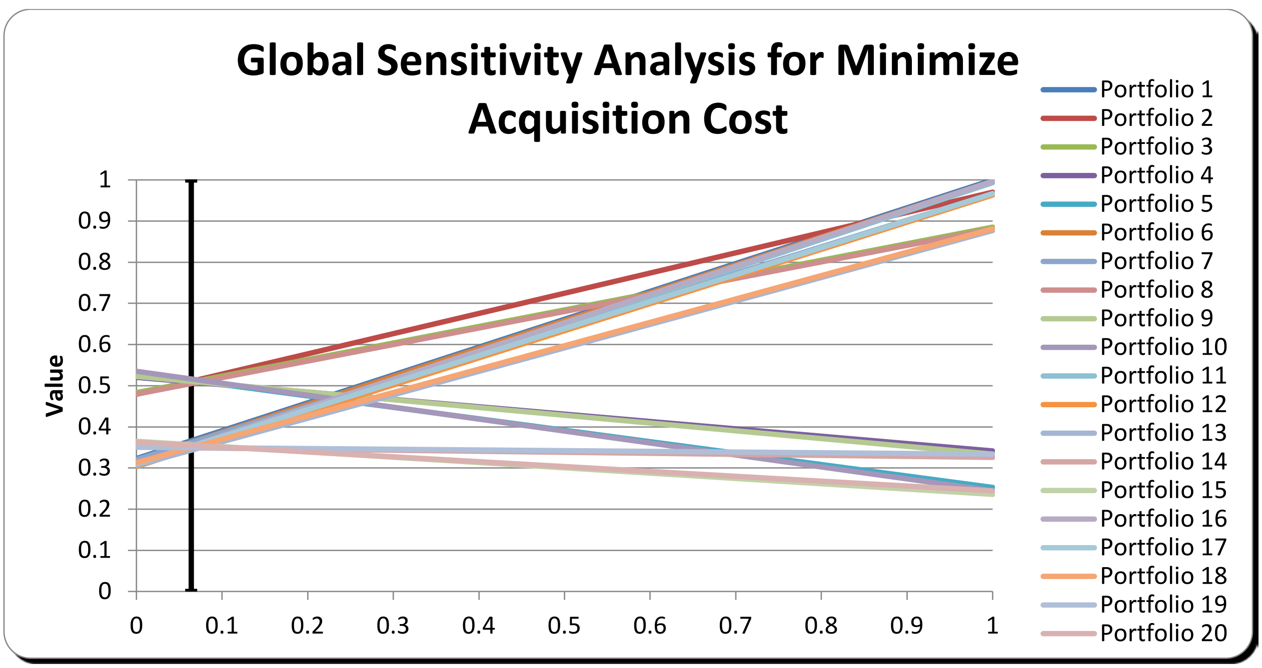
i. Maximize Apprehension Capability



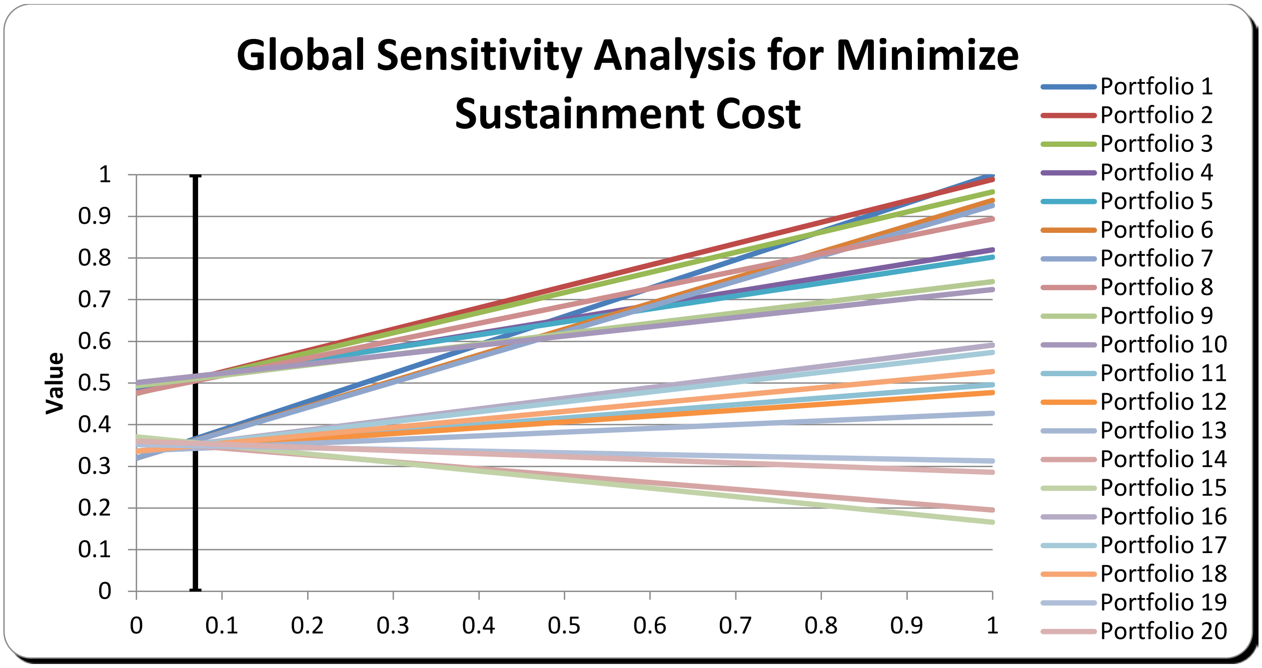
ii. Maximize Deterrence Capability



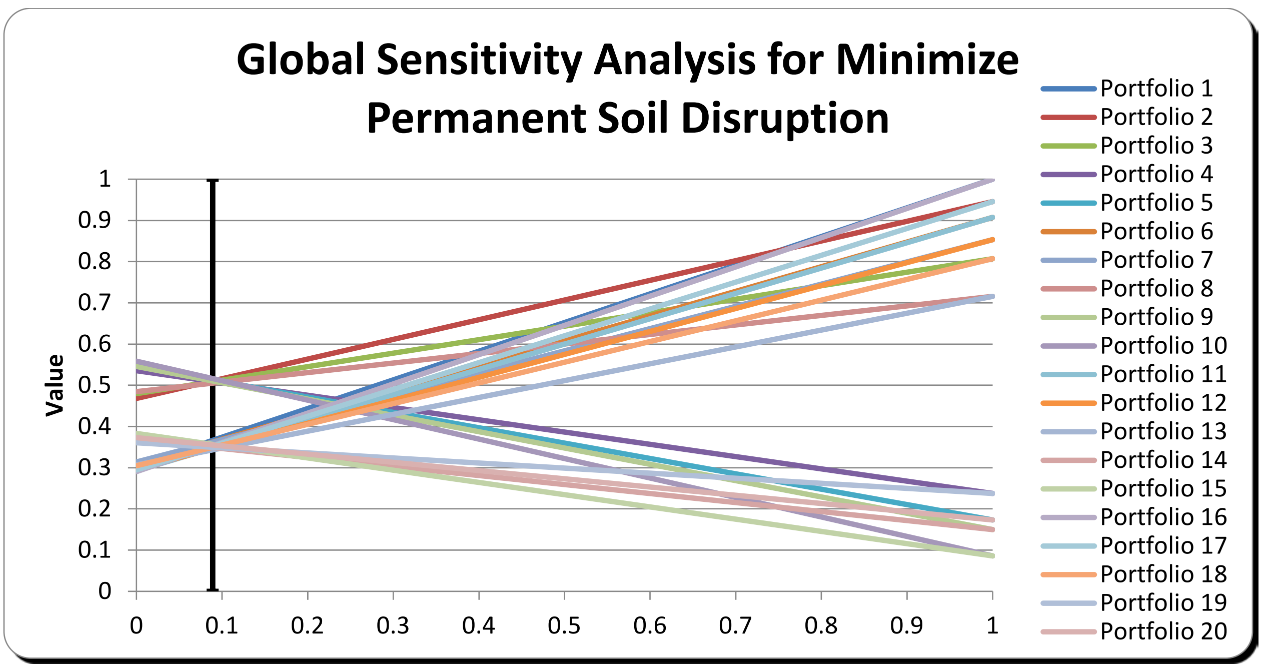
iii. Minimize Acquisition Cost



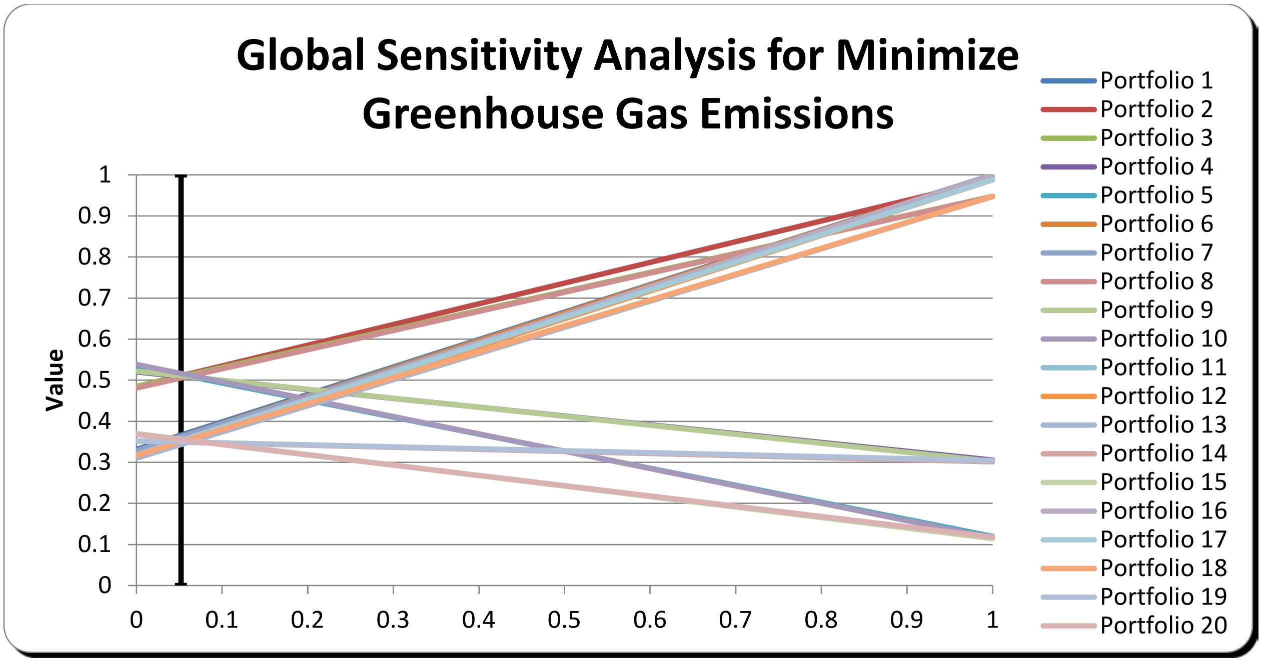
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



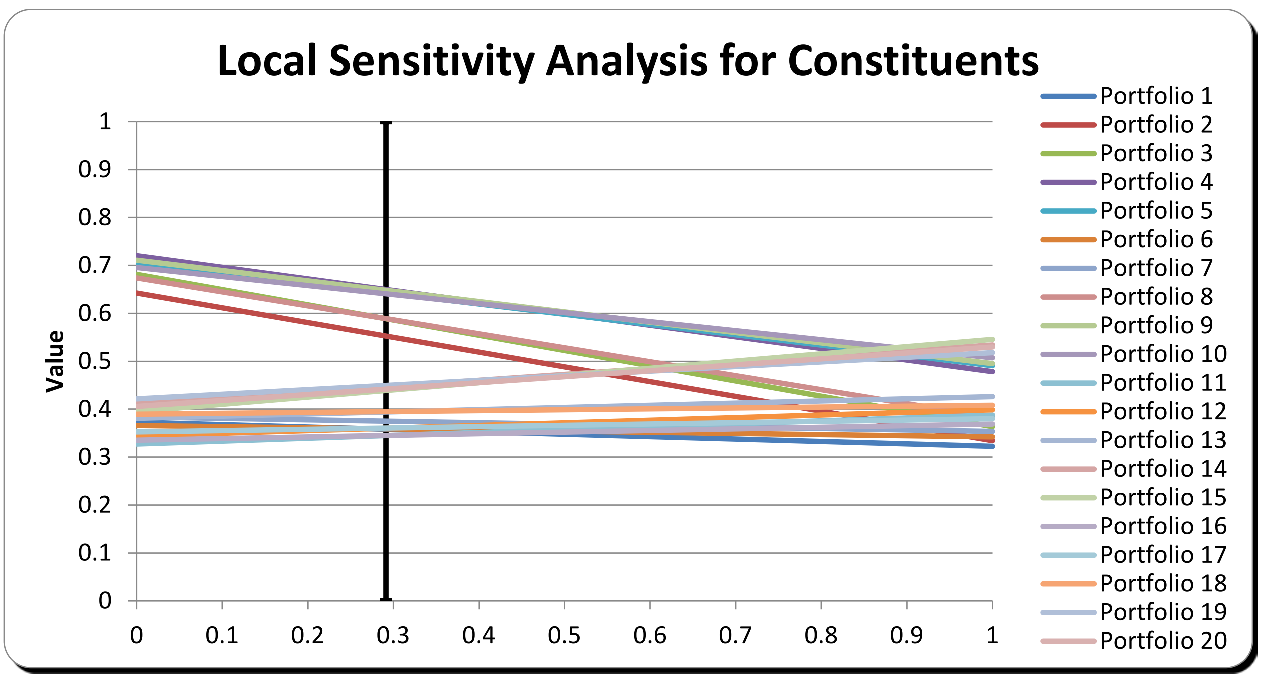
vi. Minimize Greenhouse Gas Emissions



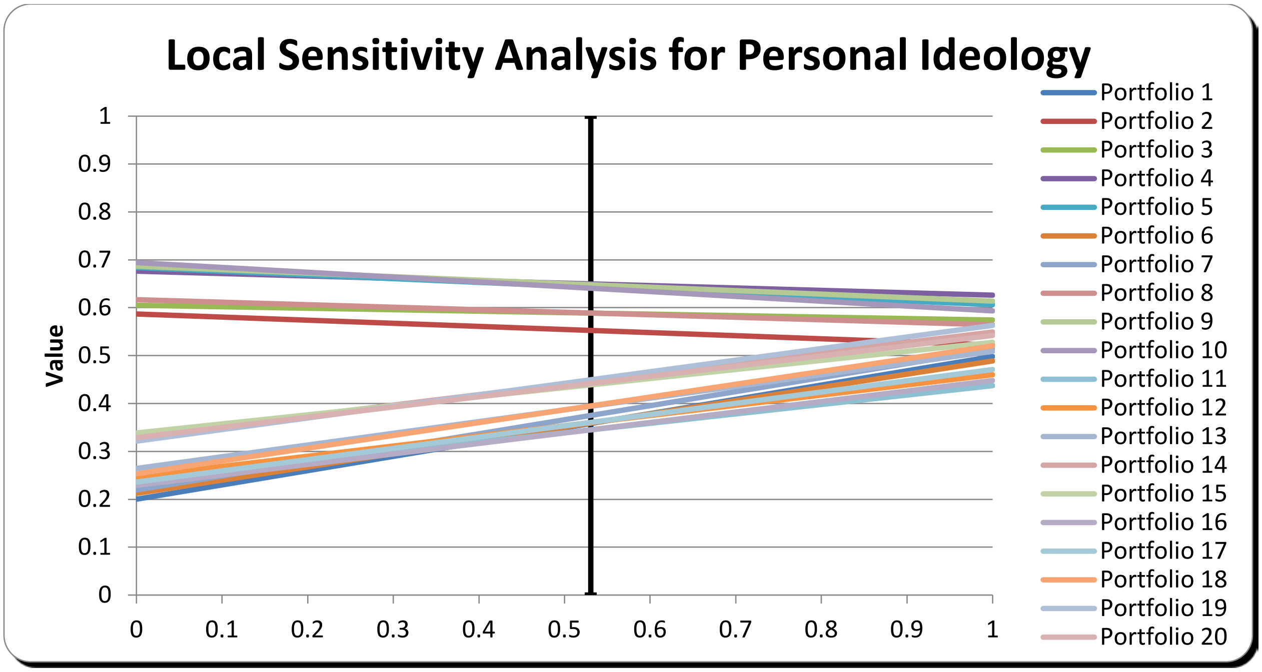
14. Gold Party DM # 4

a. Local Sensitivity Graphs

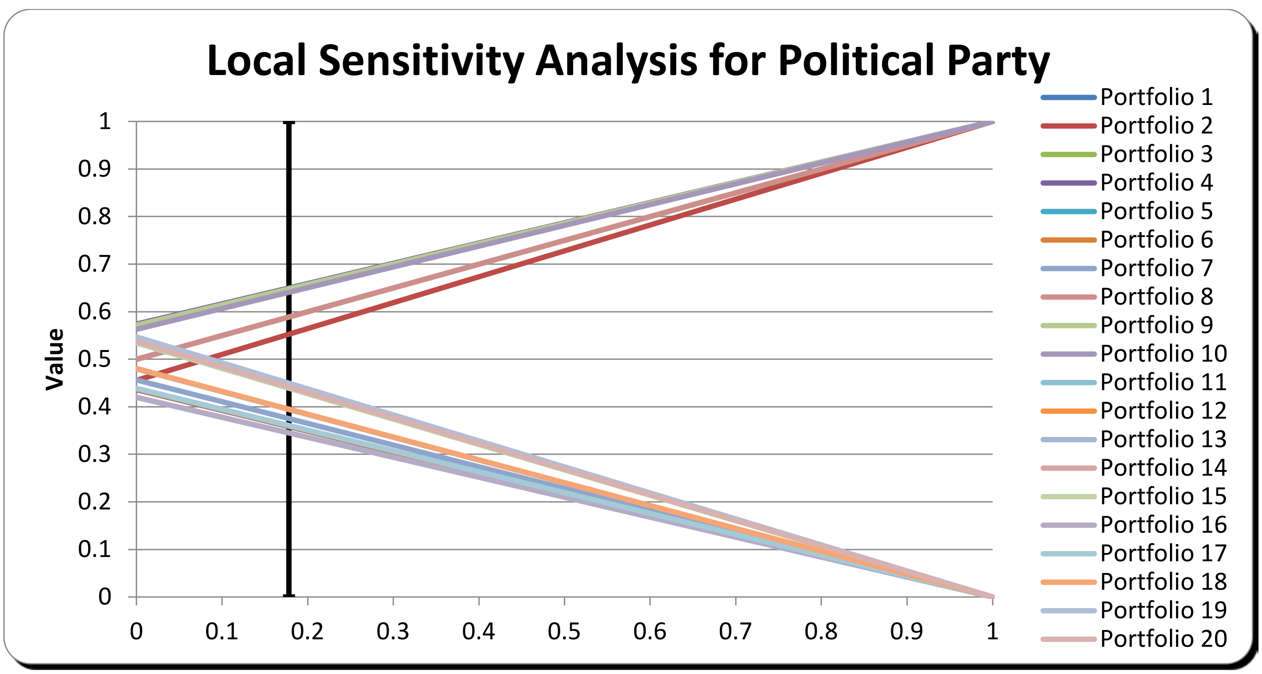
i. Constituent Satisfaction



ii. Personal Ideology

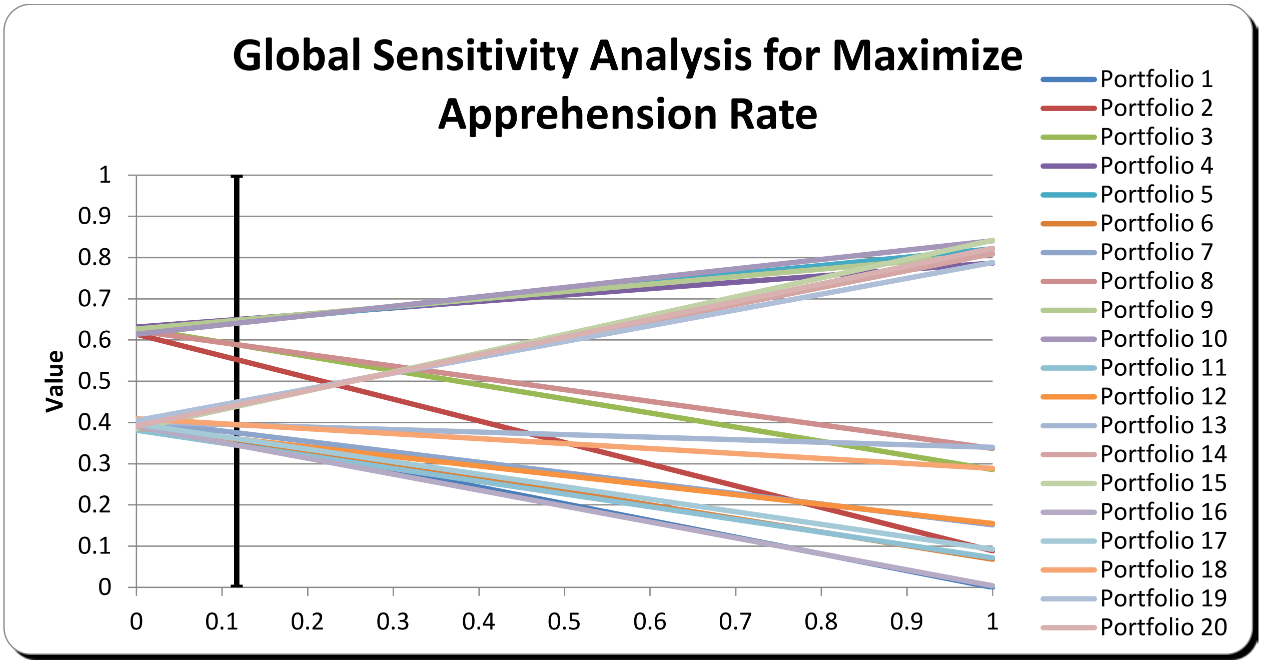


iii. Party Leader Support

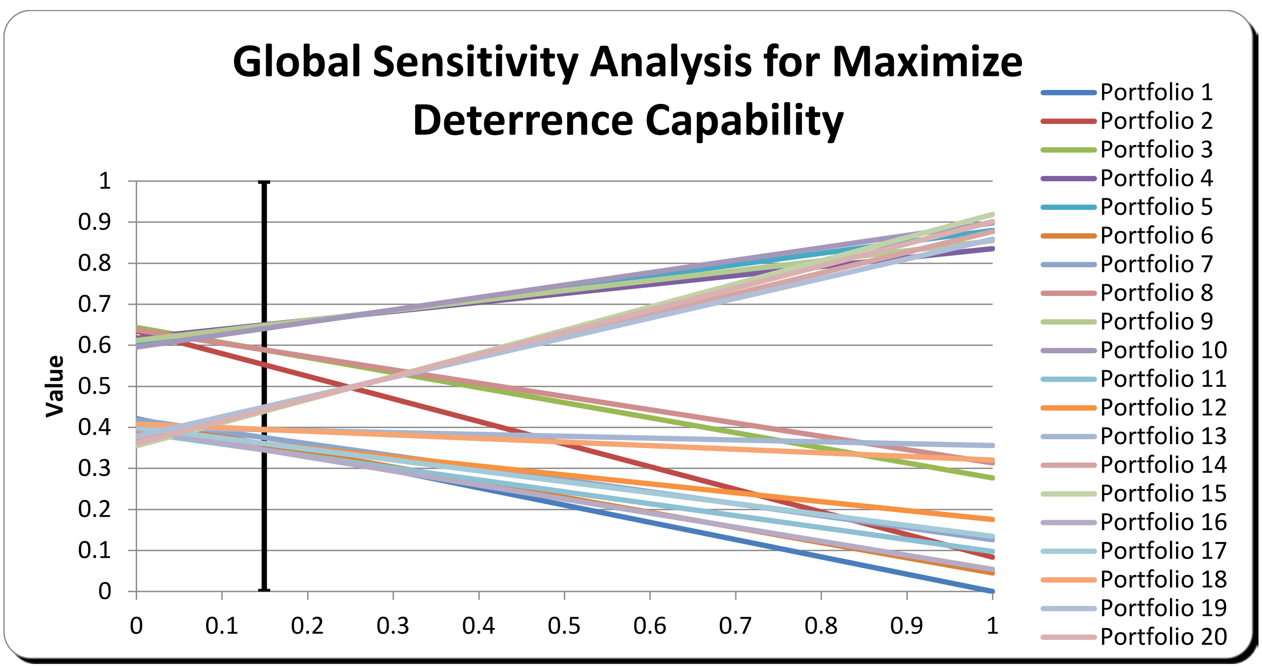


b. Global Sensitivity Graphs

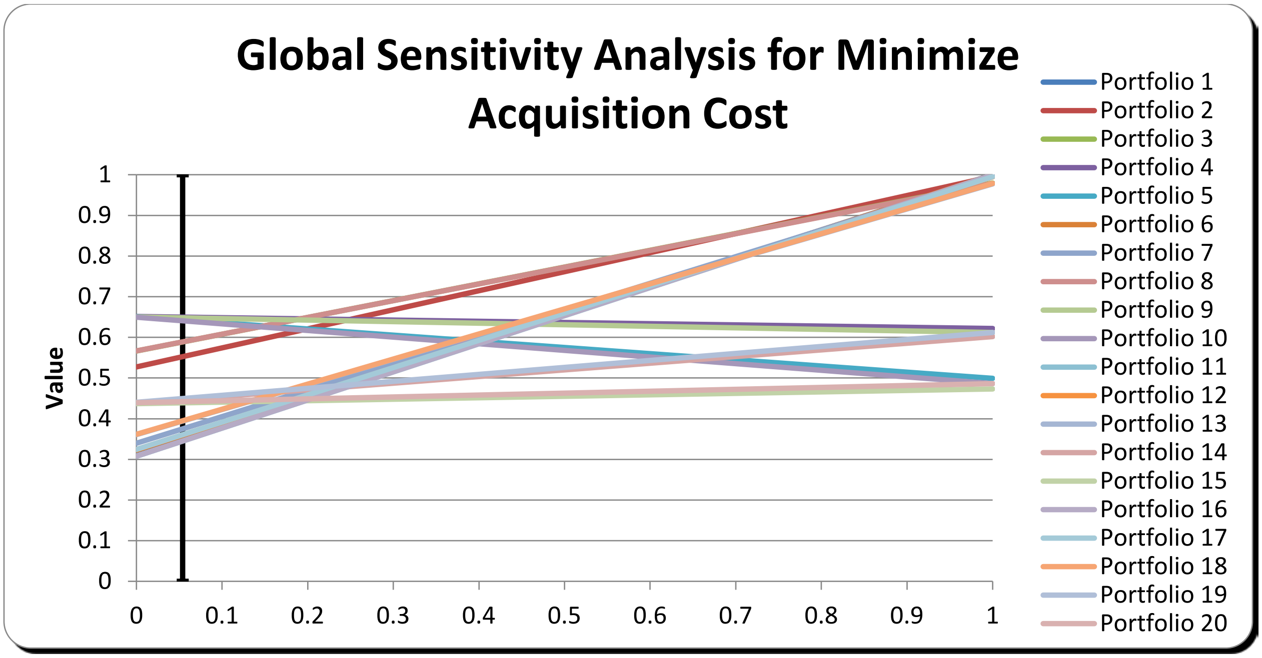
i. Maximize Apprehension Capability



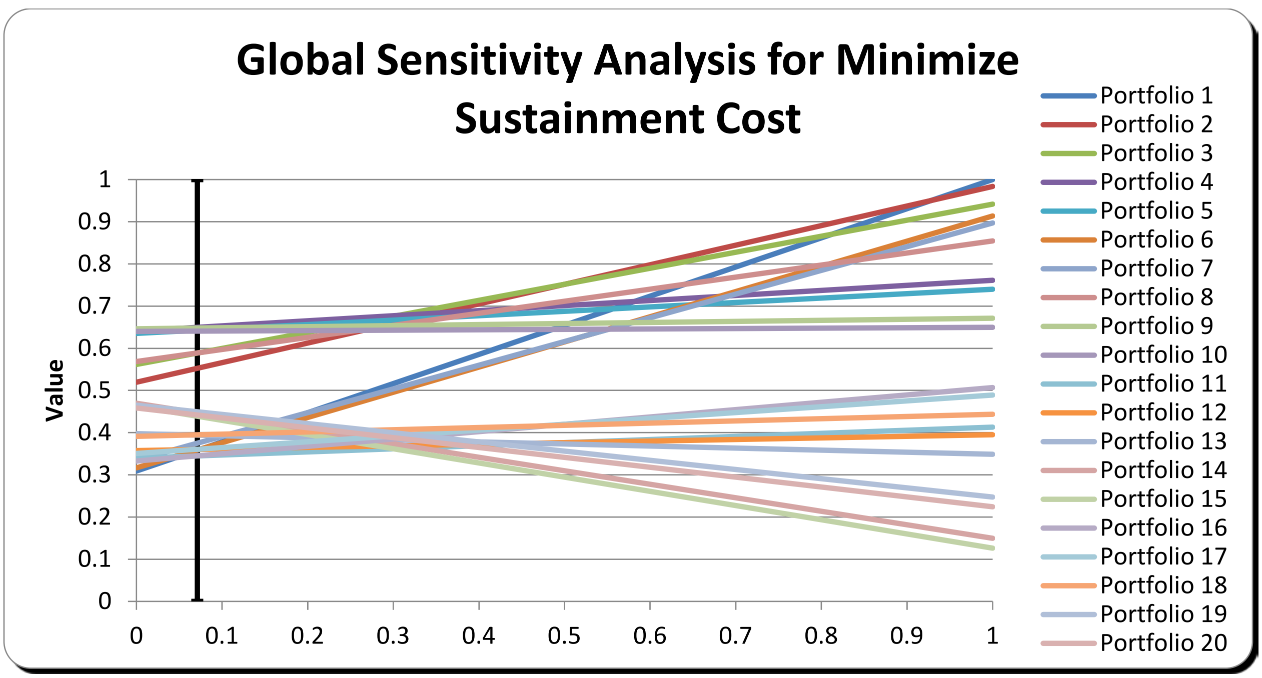
ii. Maximize Deterrence Capability



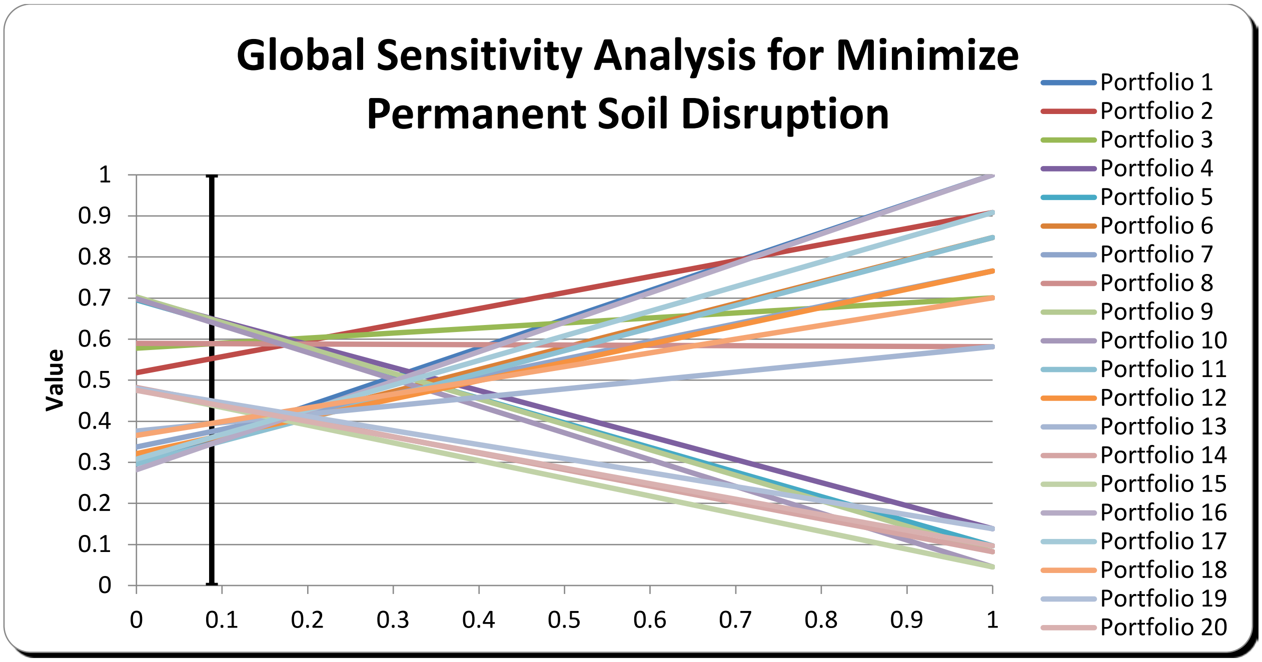
iii. Minimize Acquisition Cost



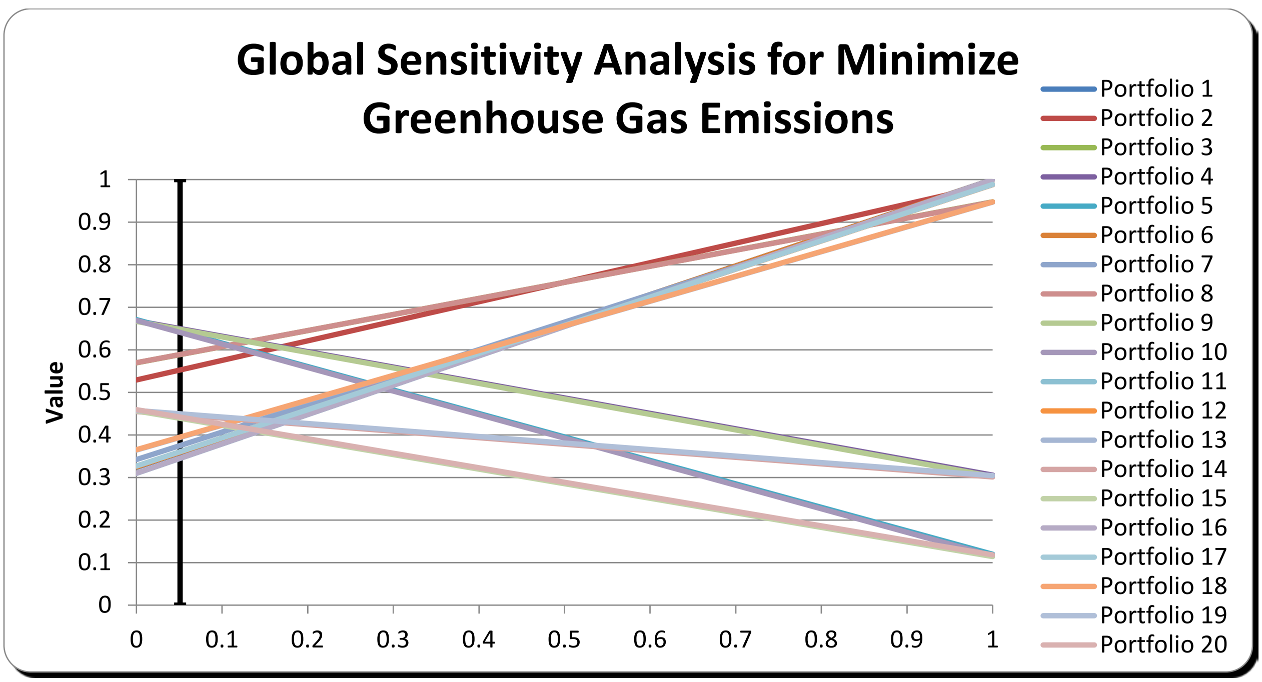
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



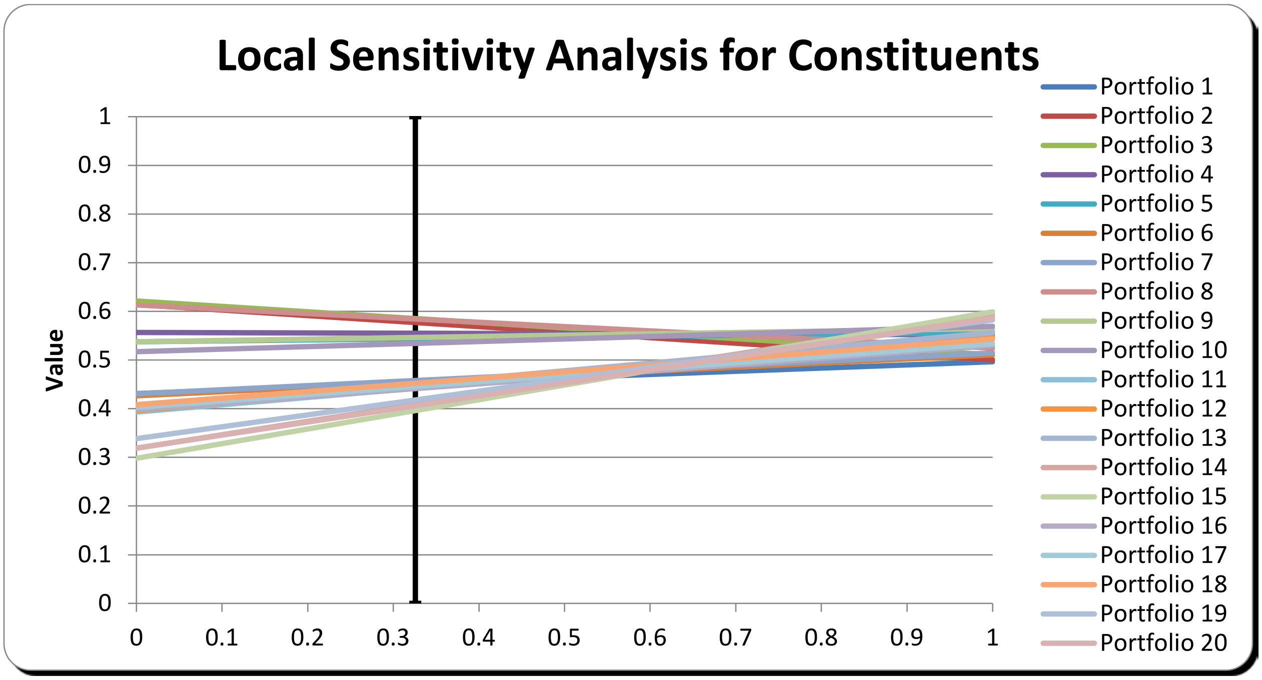
vi. Minimize Greenhouse Gas Emissions



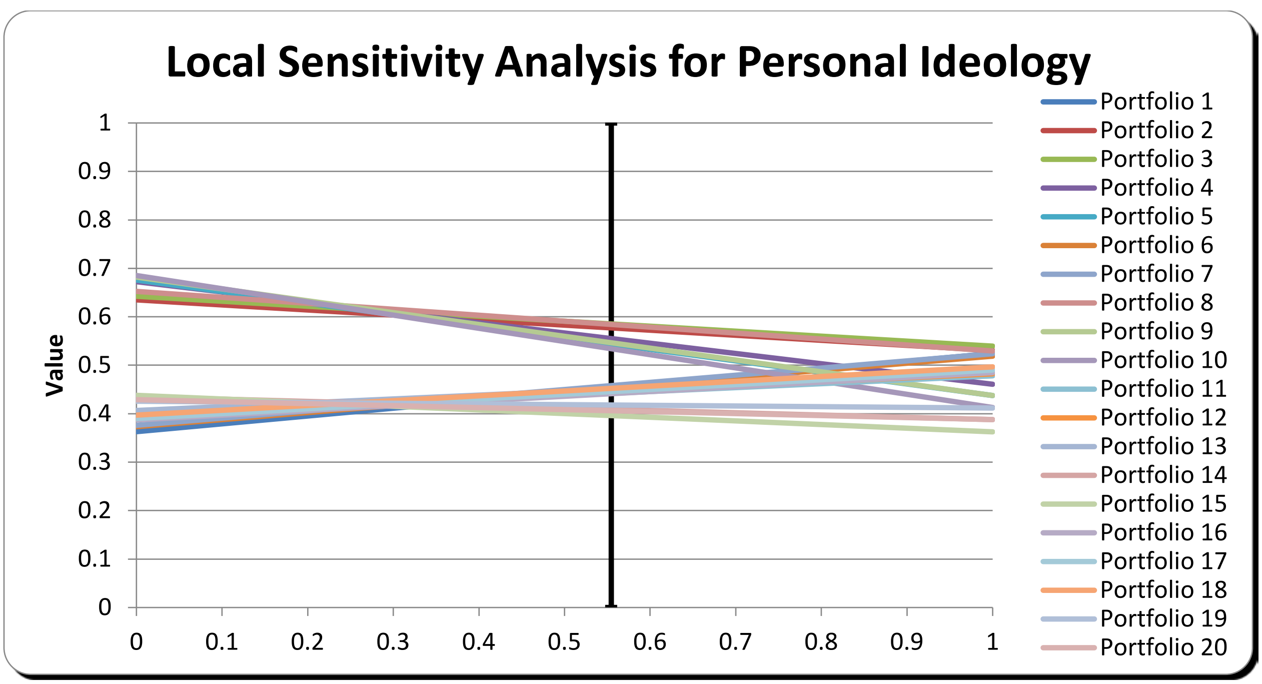
15. Gold Party DM # 5

a. Local Sensitivity Graphs

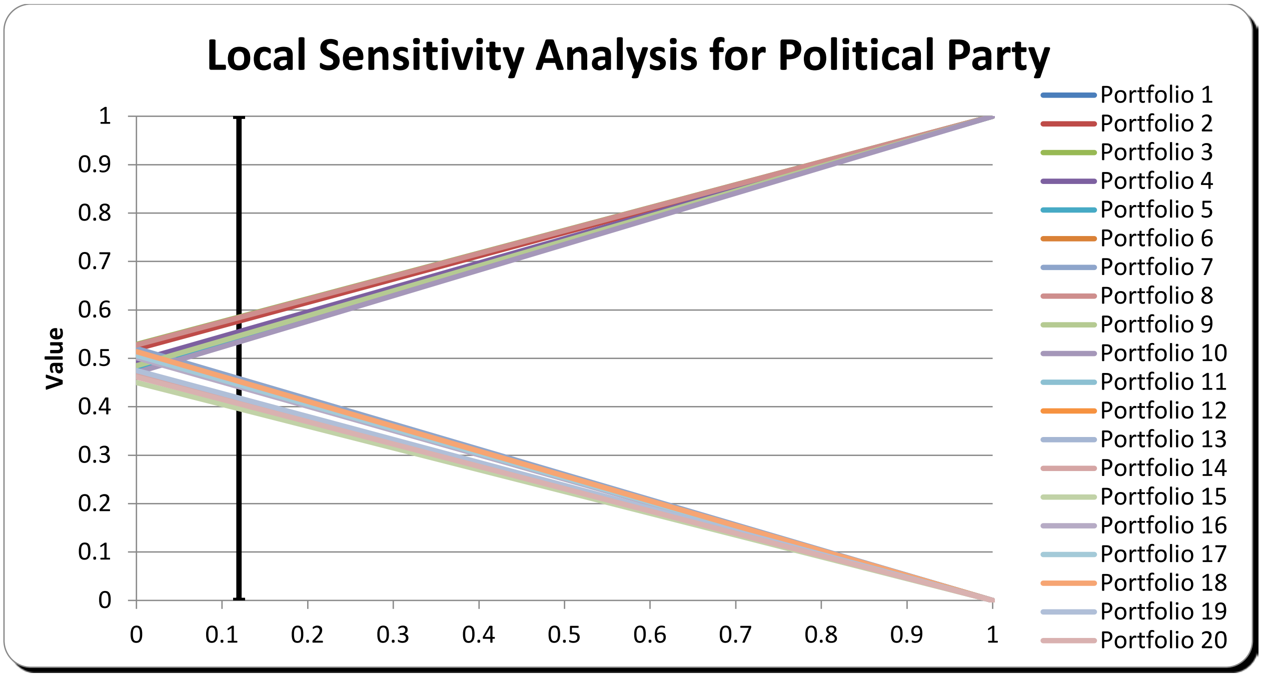
i. Constituent Satisfaction



ii. Personal Ideology

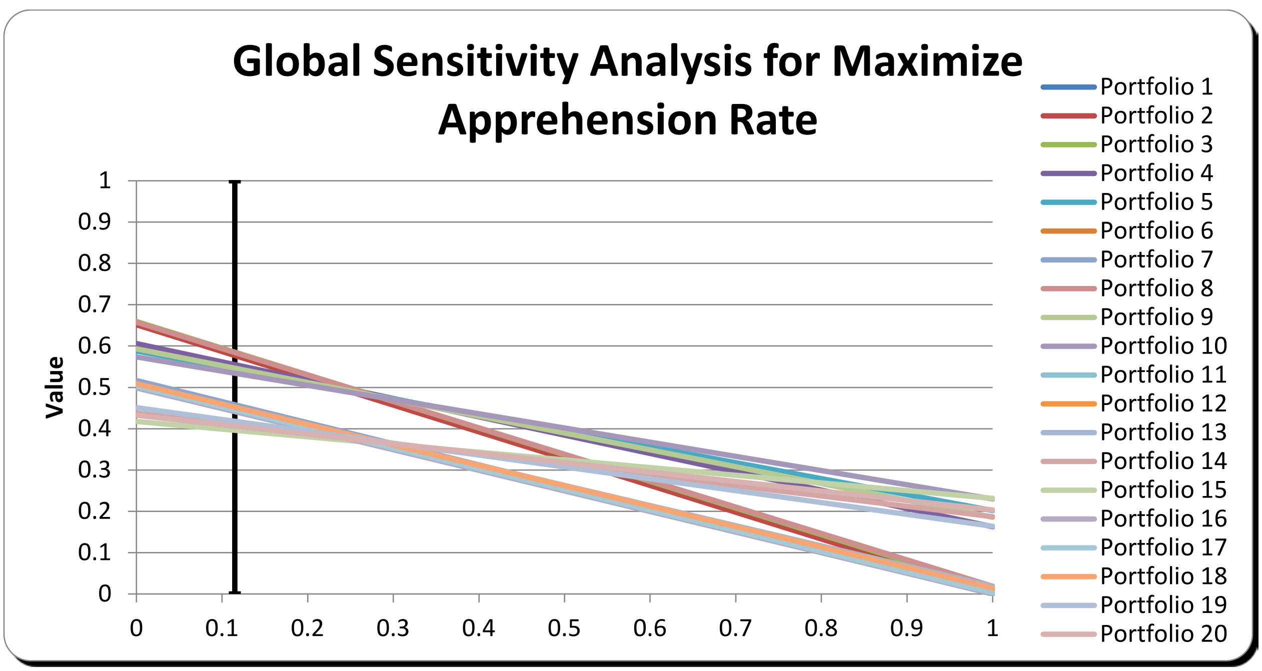


iii. Party Leader Support

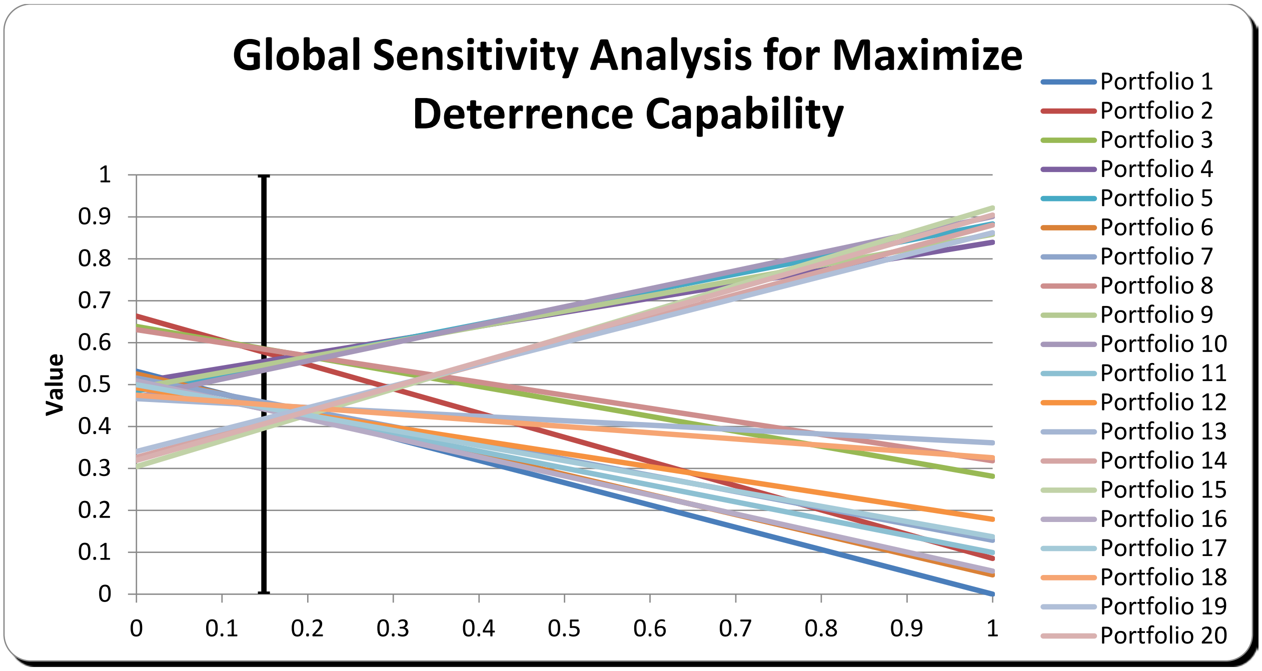


b. Global Sensitivity Graphs

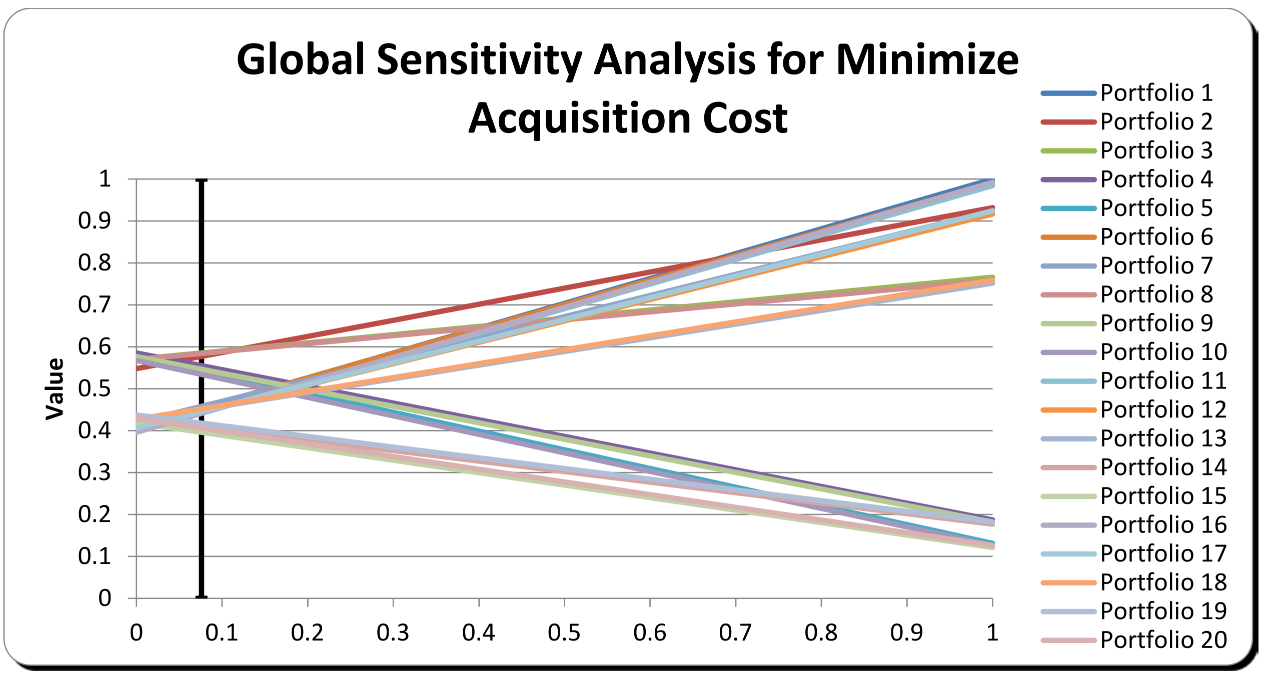
i. Maximize Apprehension Capability



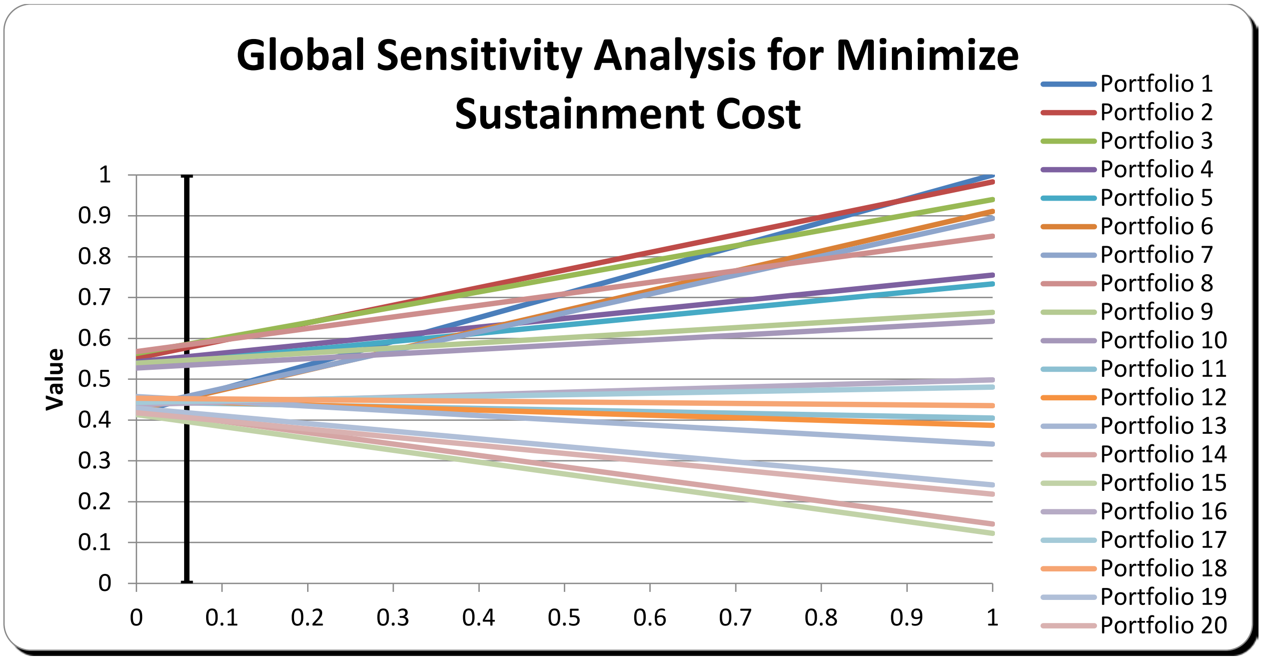
ii. Maximize Deterrence Capability



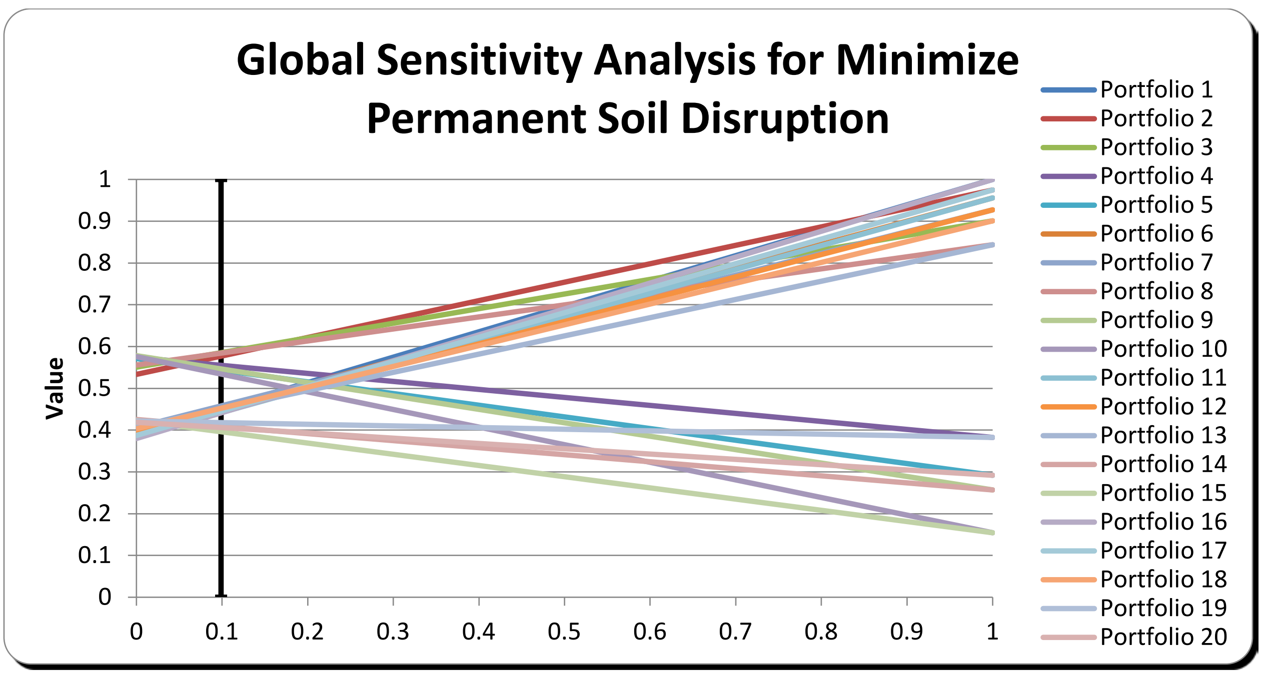
iii. Minimize Acquisition Cost



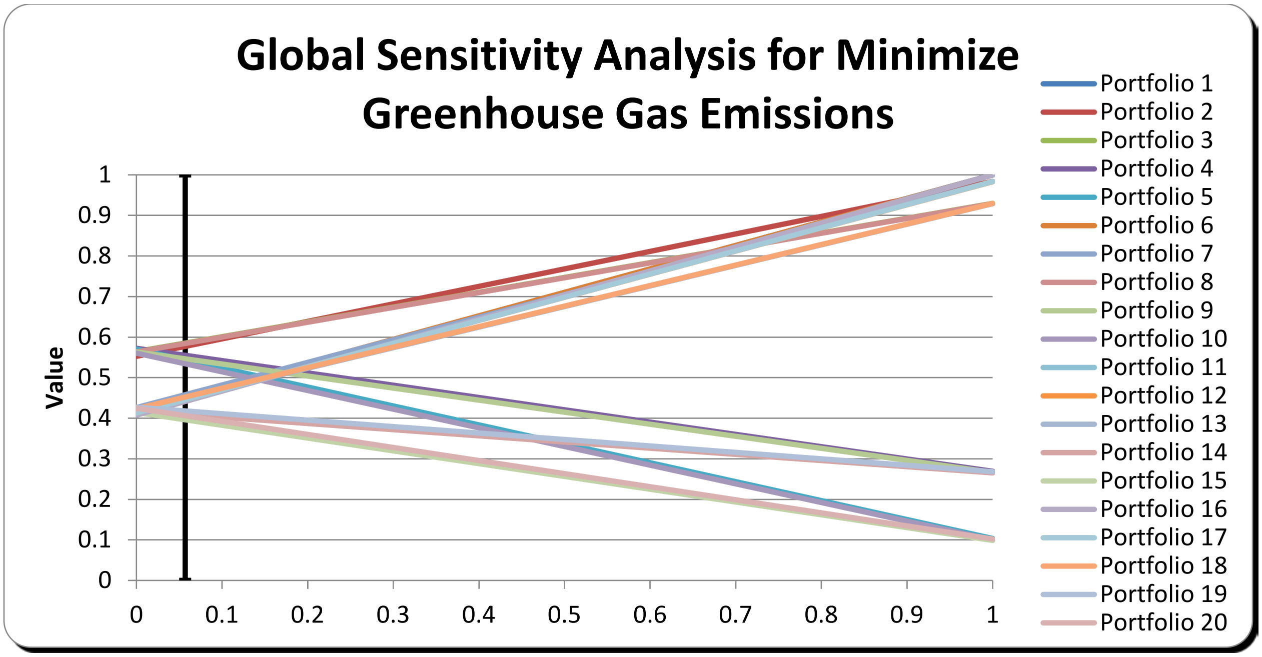
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



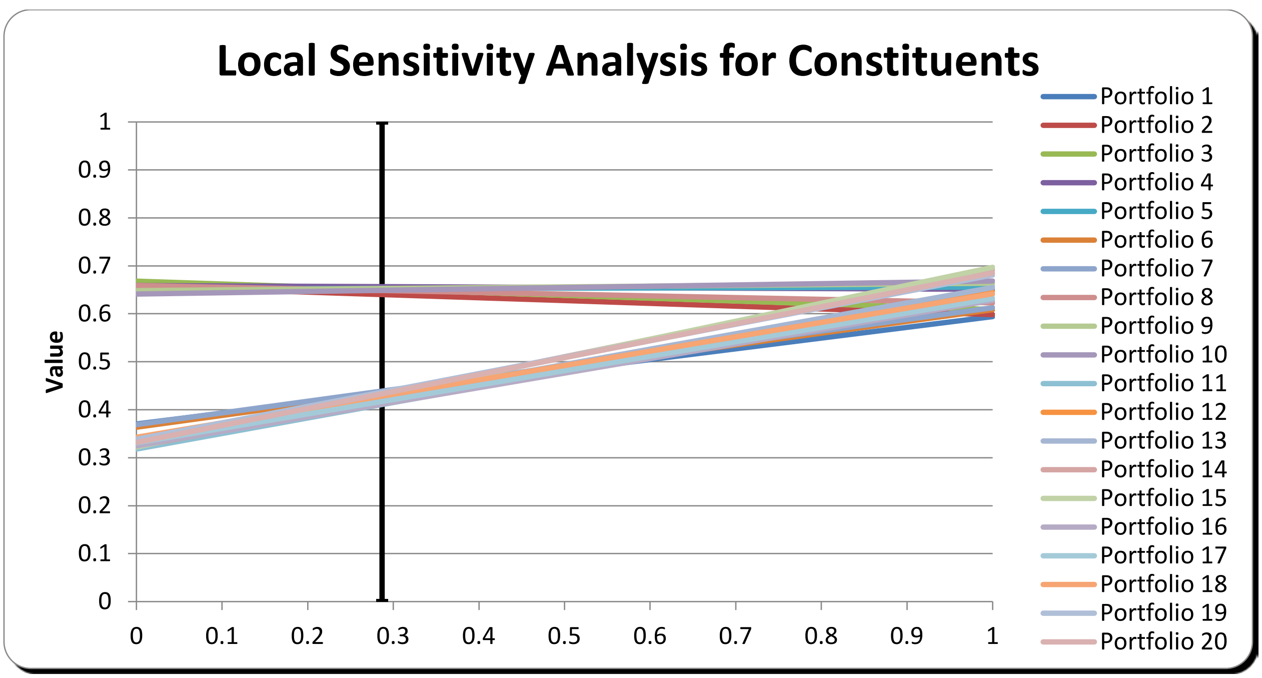
vi. Minimize Greenhouse Gas Emissions



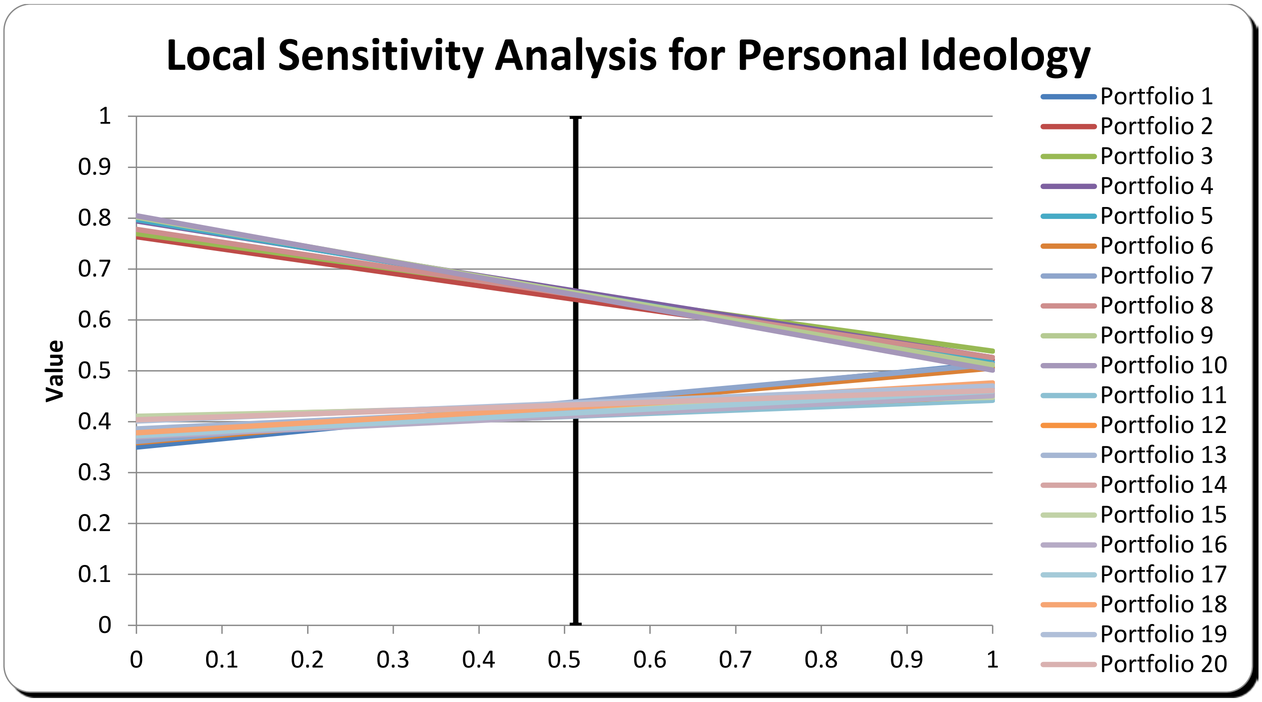
16. Gold Party DM # 6

a. Local Sensitivity Graphs

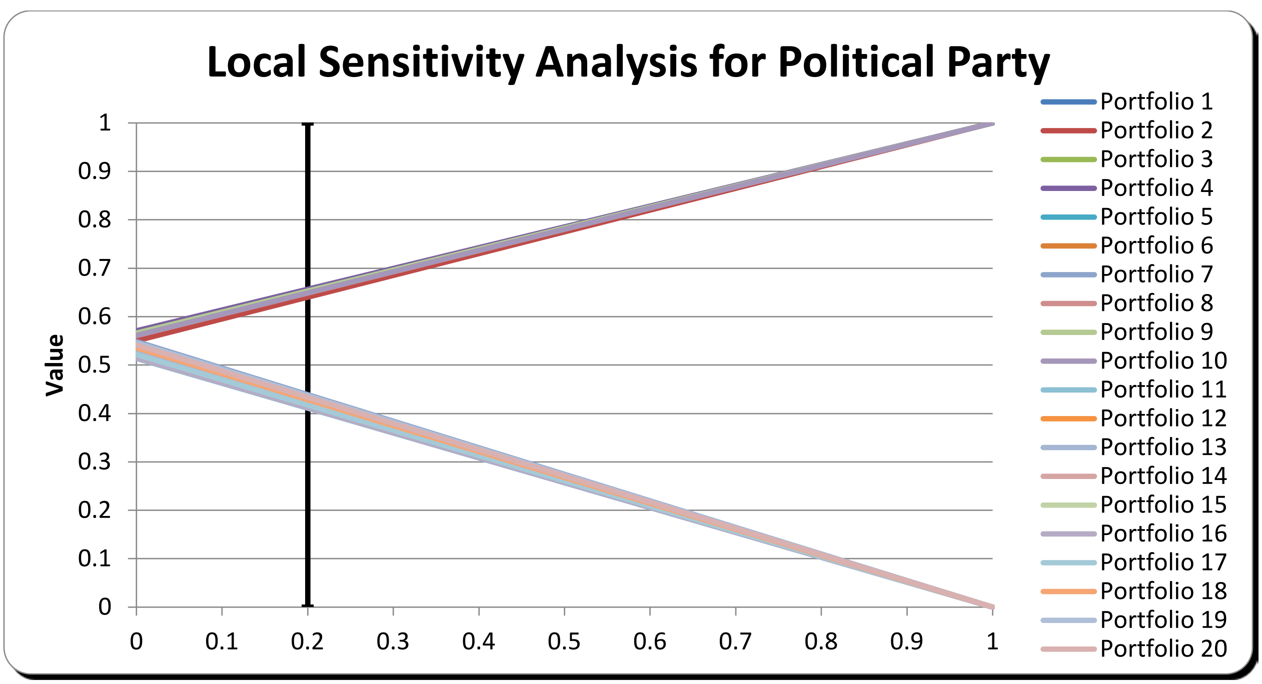
i. Constituent Satisfaction



ii. Personal Ideology

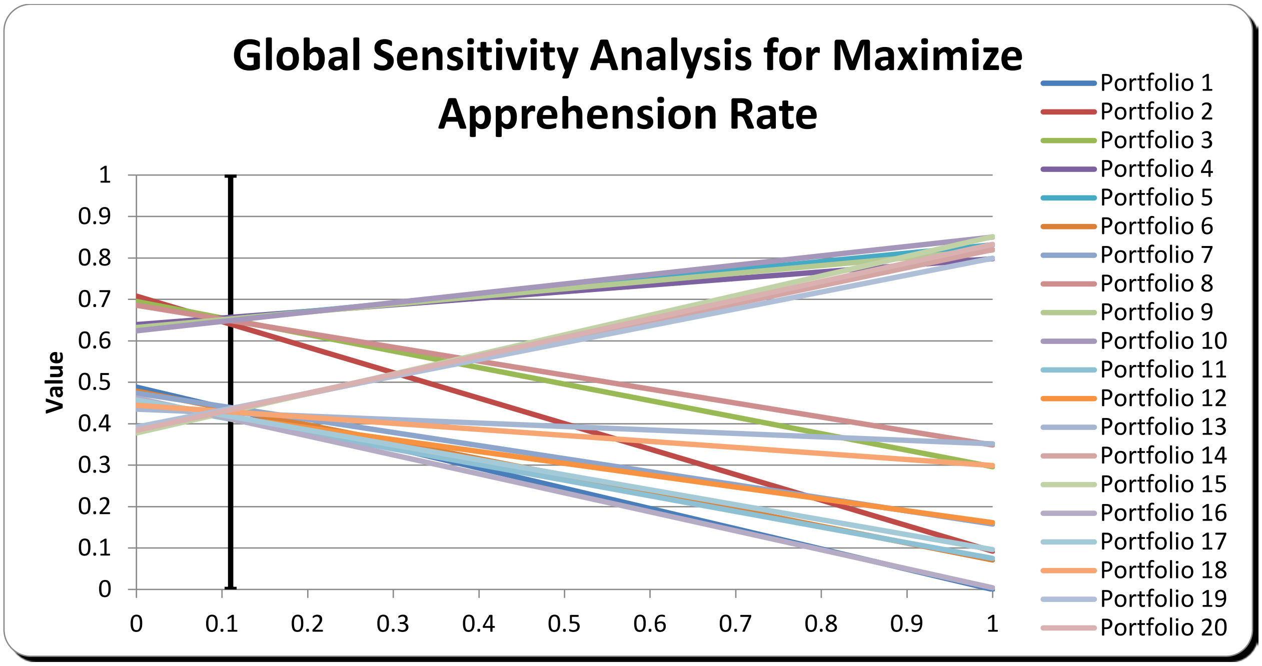


iii. Party Leader Support

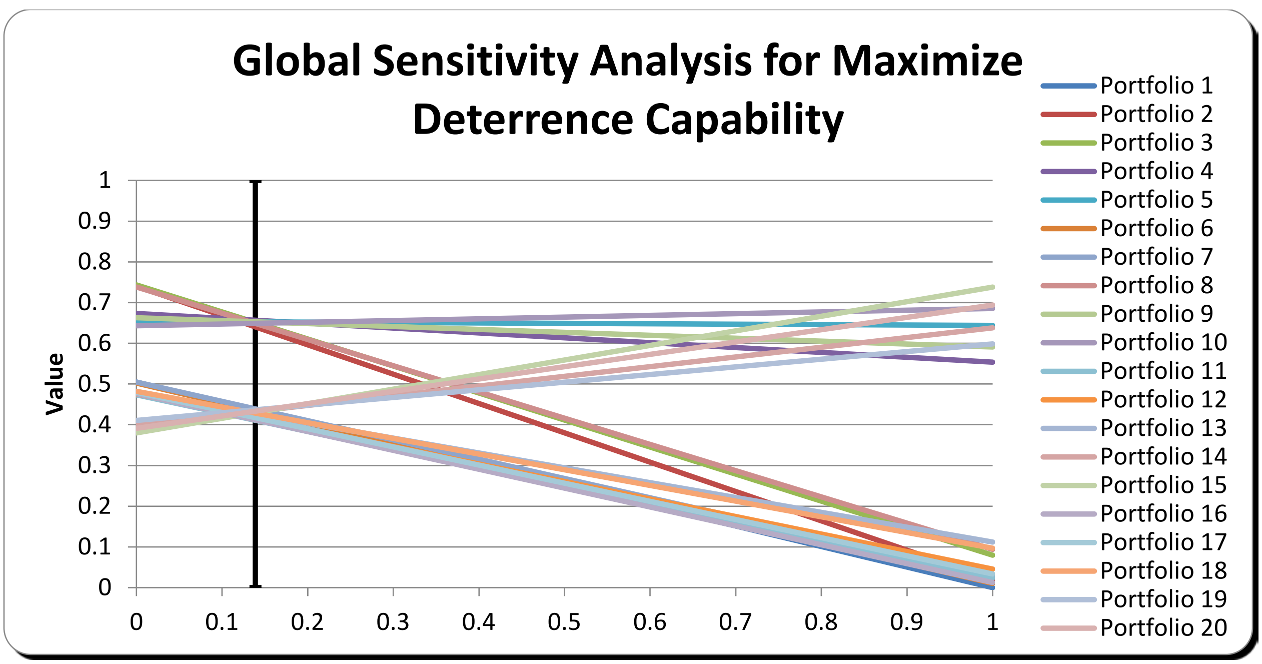


b. Global Sensitivity Graphs

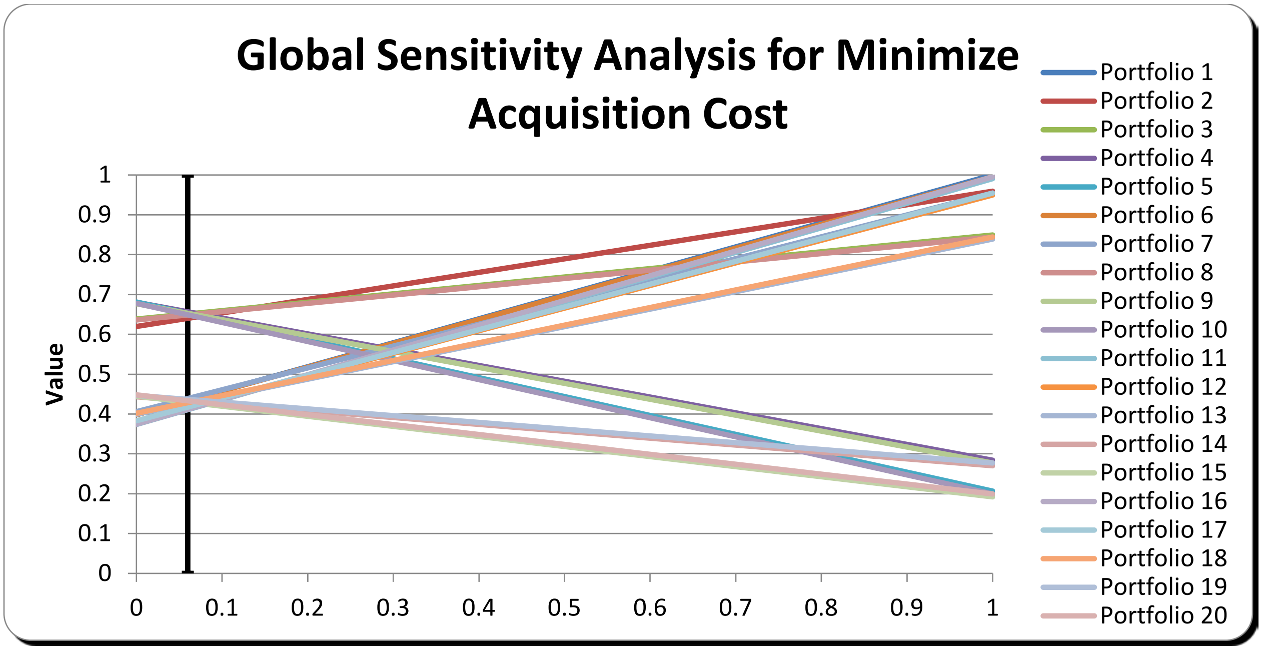
i. Maximize Apprehension Capability



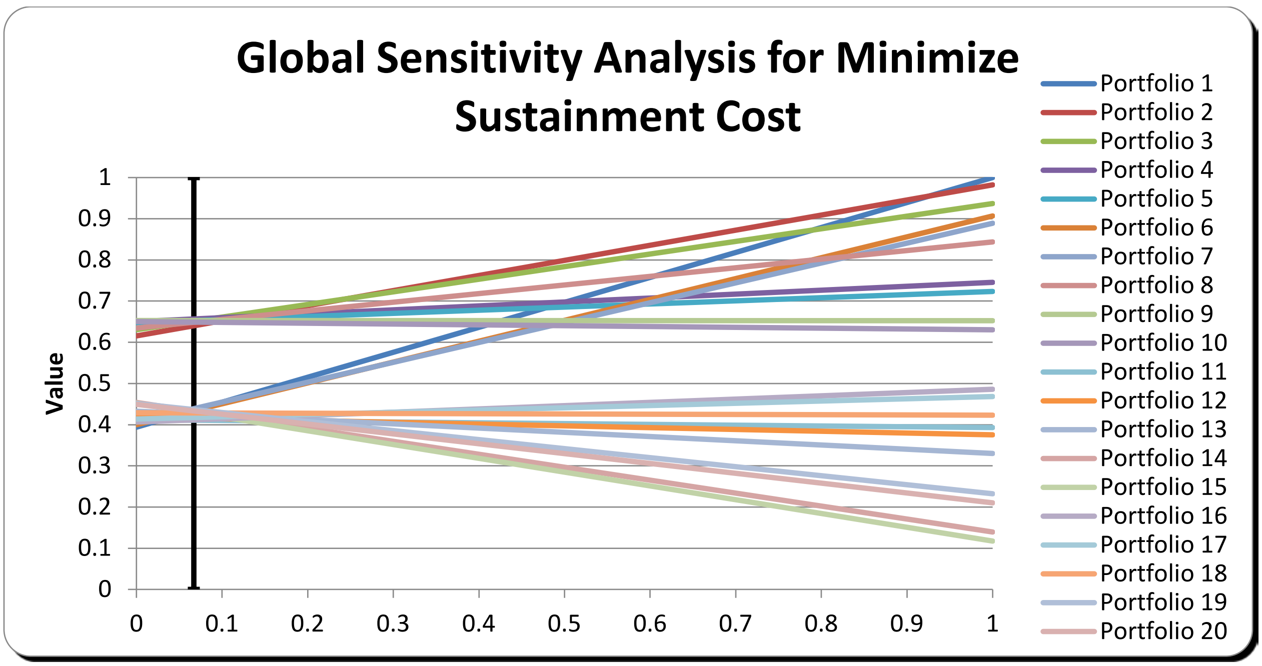
ii. Maximize Deterrence Capability



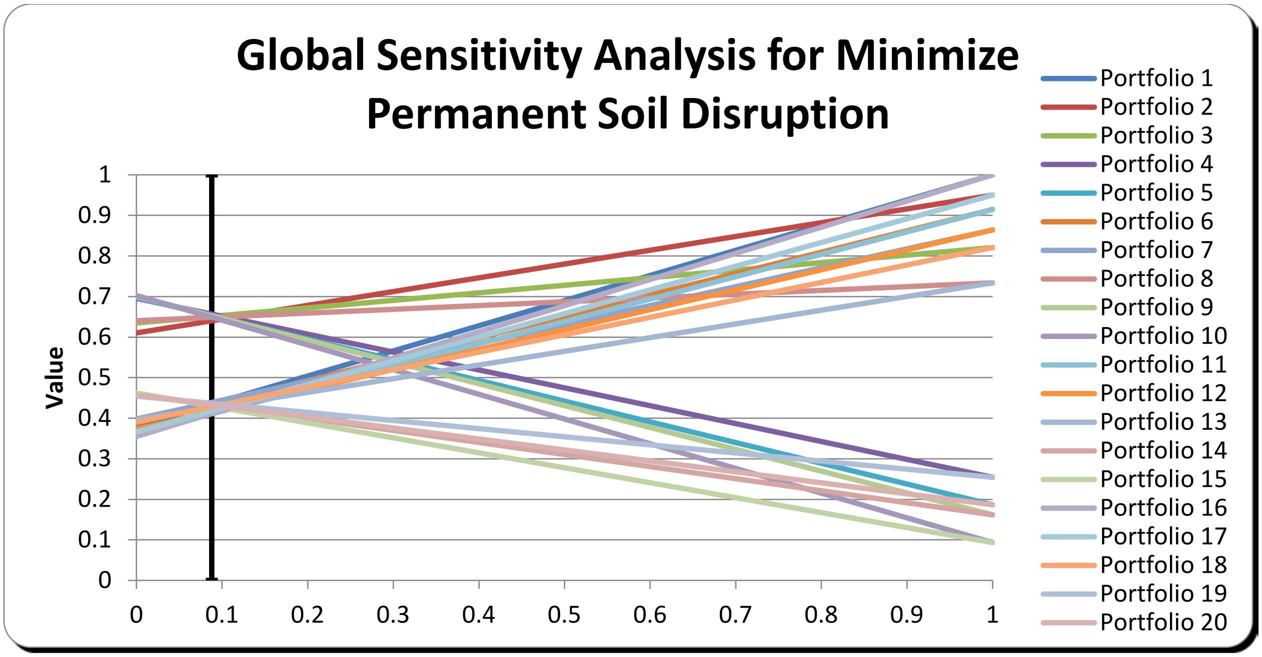
iii. Minimize Acquisition Cost



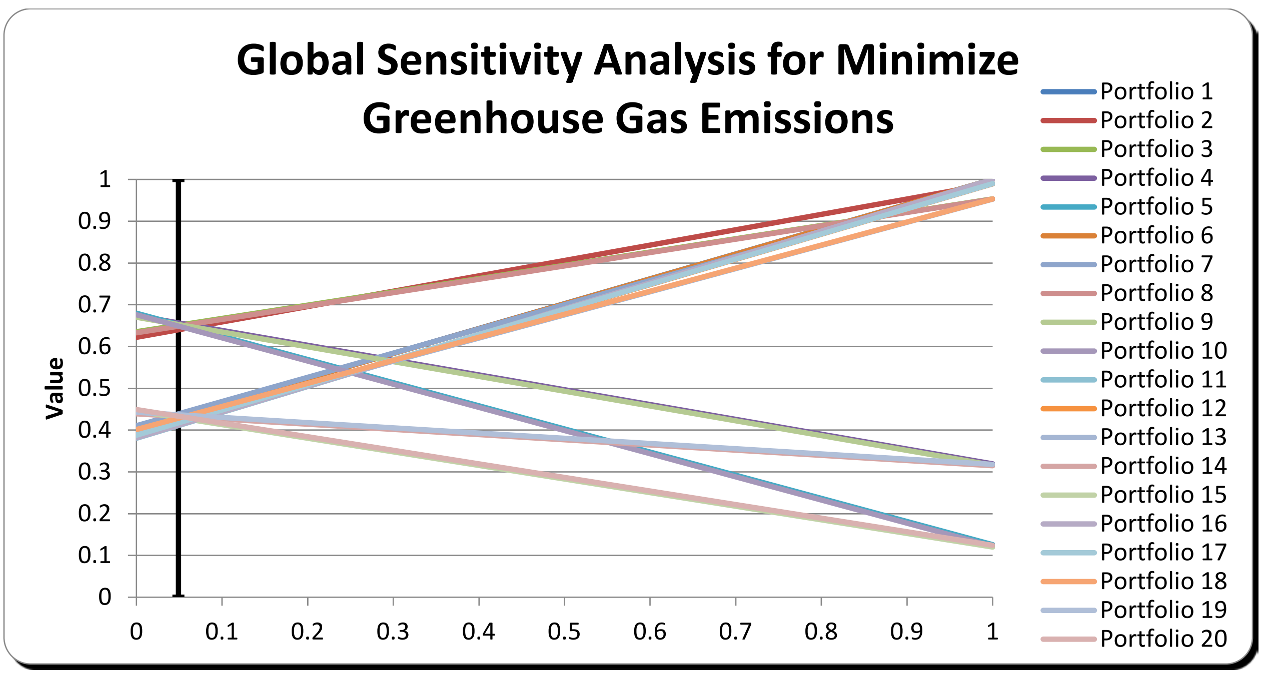
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



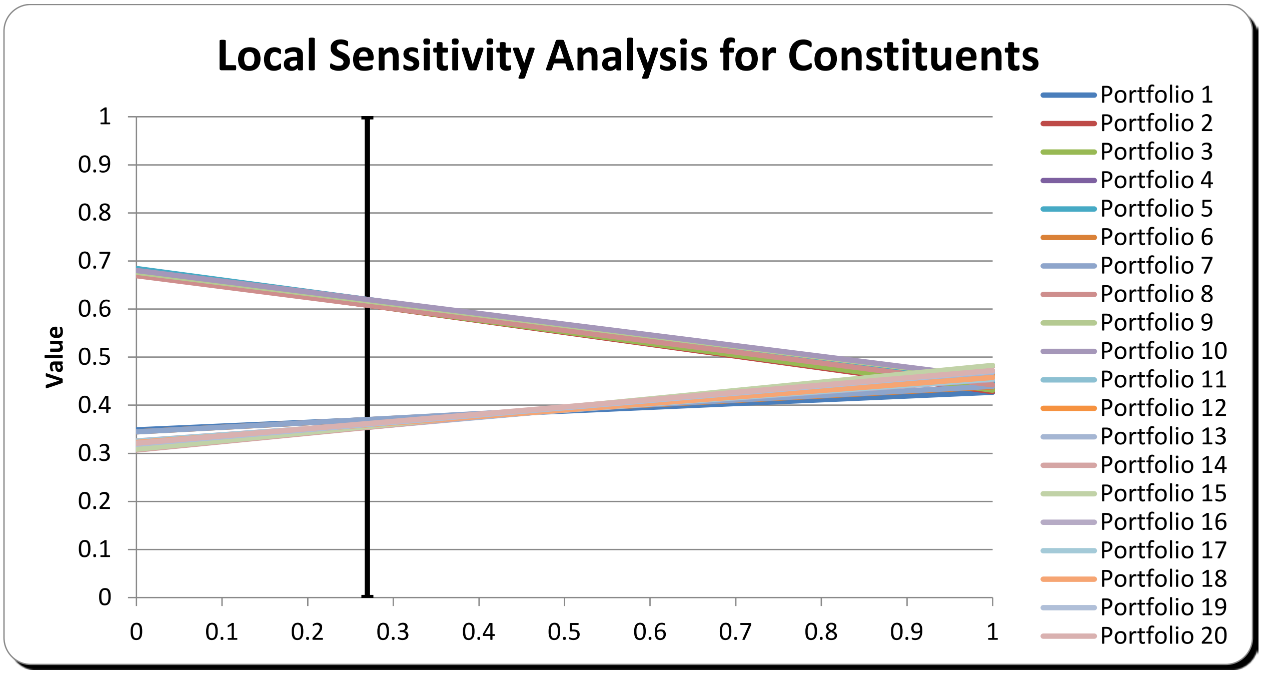
vi. Minimize Greenhouse Gas Emissions



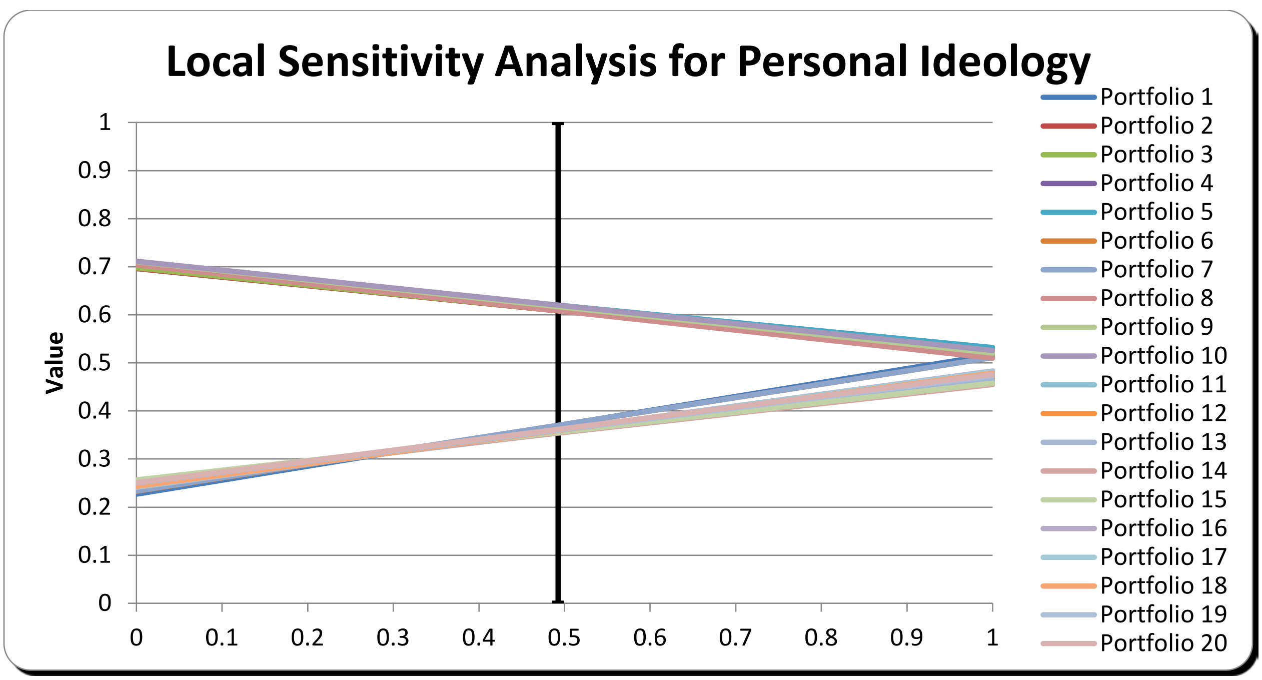
17. Gold Party DM # 7

a. Local Sensitivity Graphs

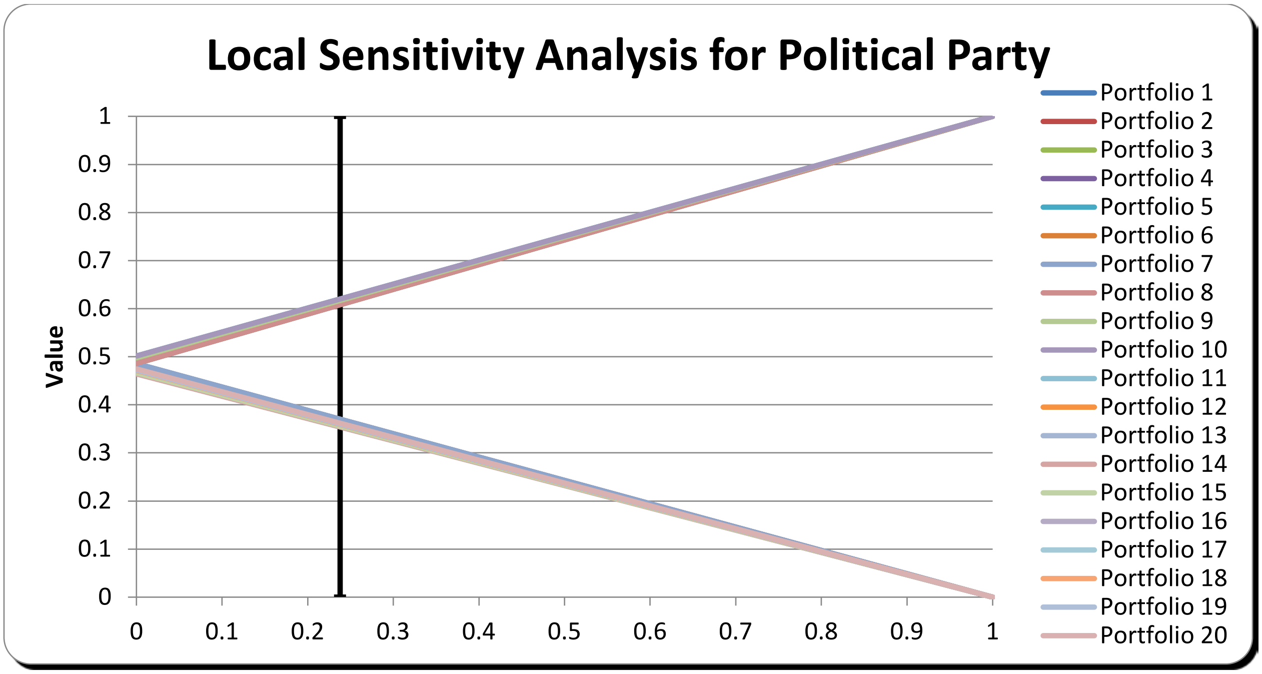
i. Constituent Satisfaction



ii. Personal Ideology

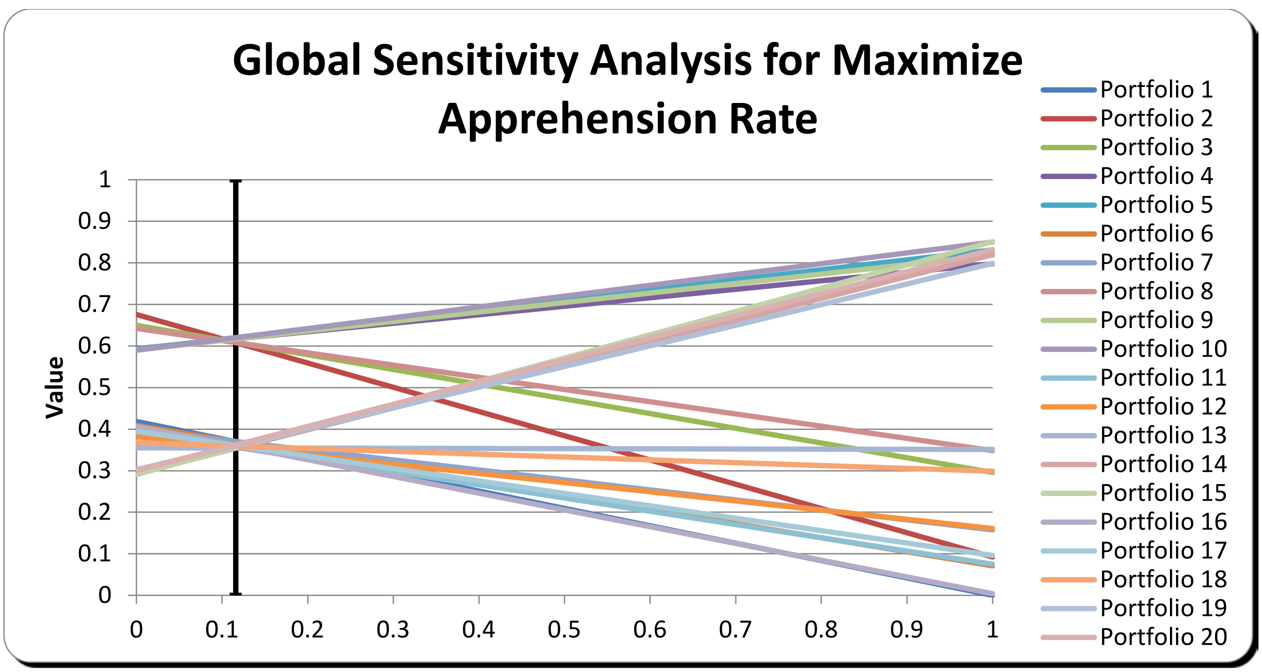


iii. Party Leader Support

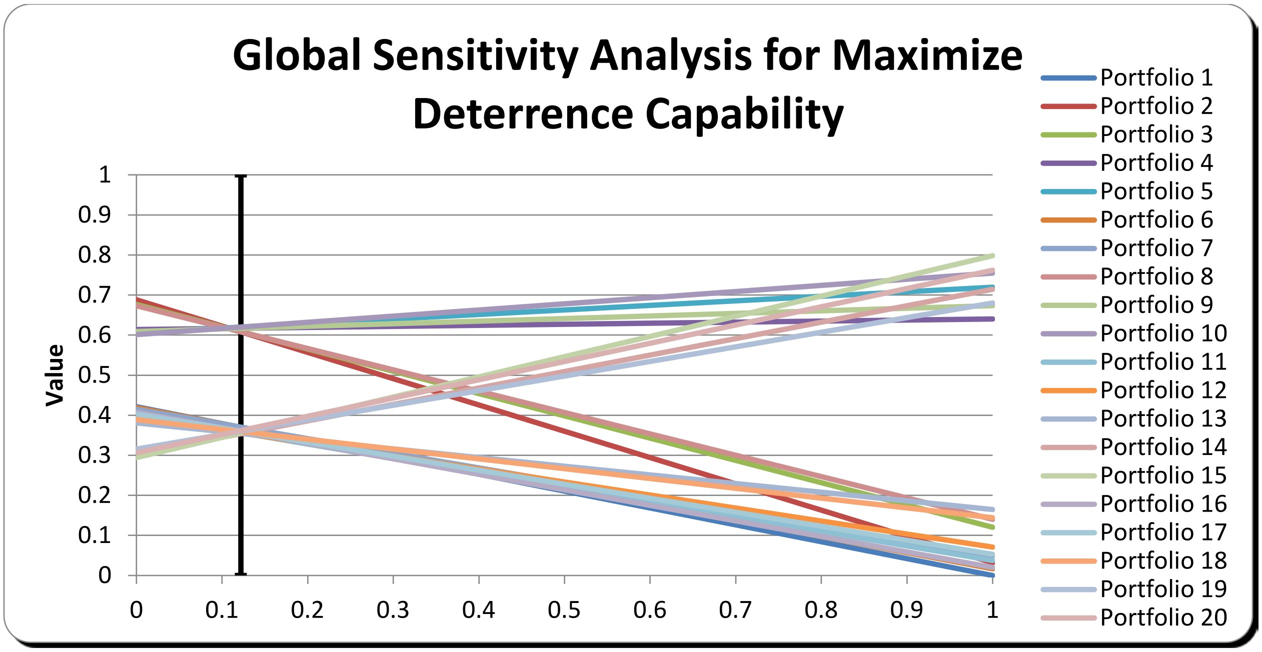


b. Global Sensitivity Graphs

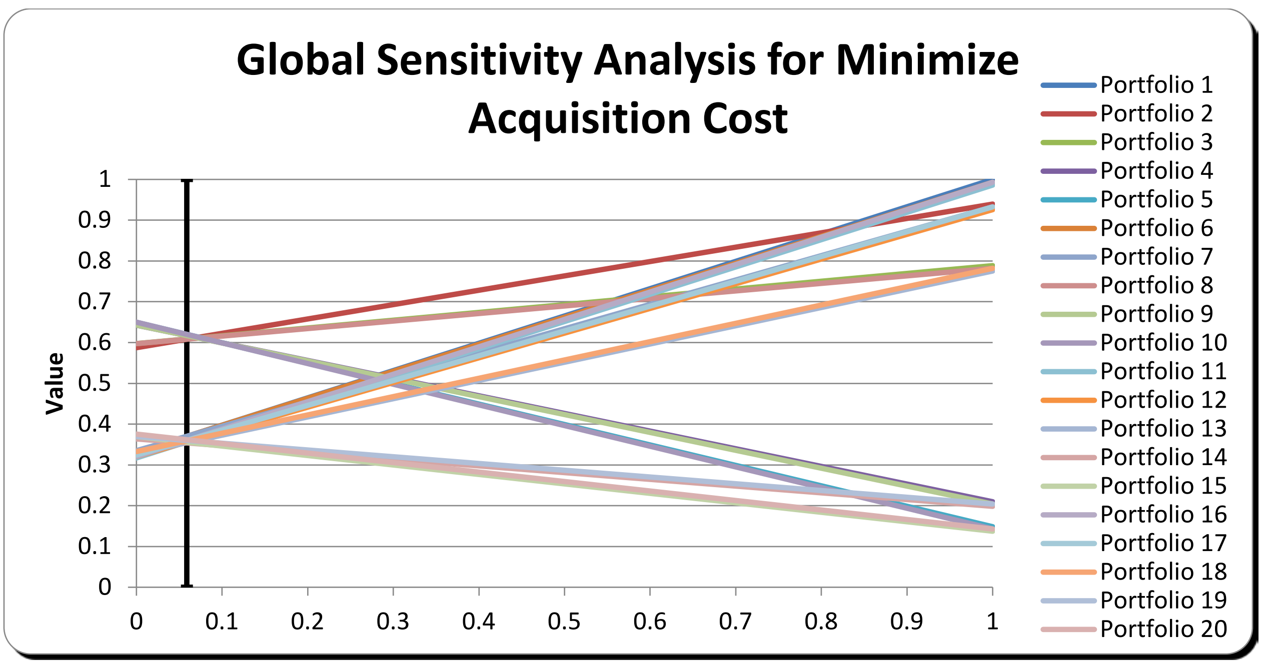
i. Maximize Apprehension Capability



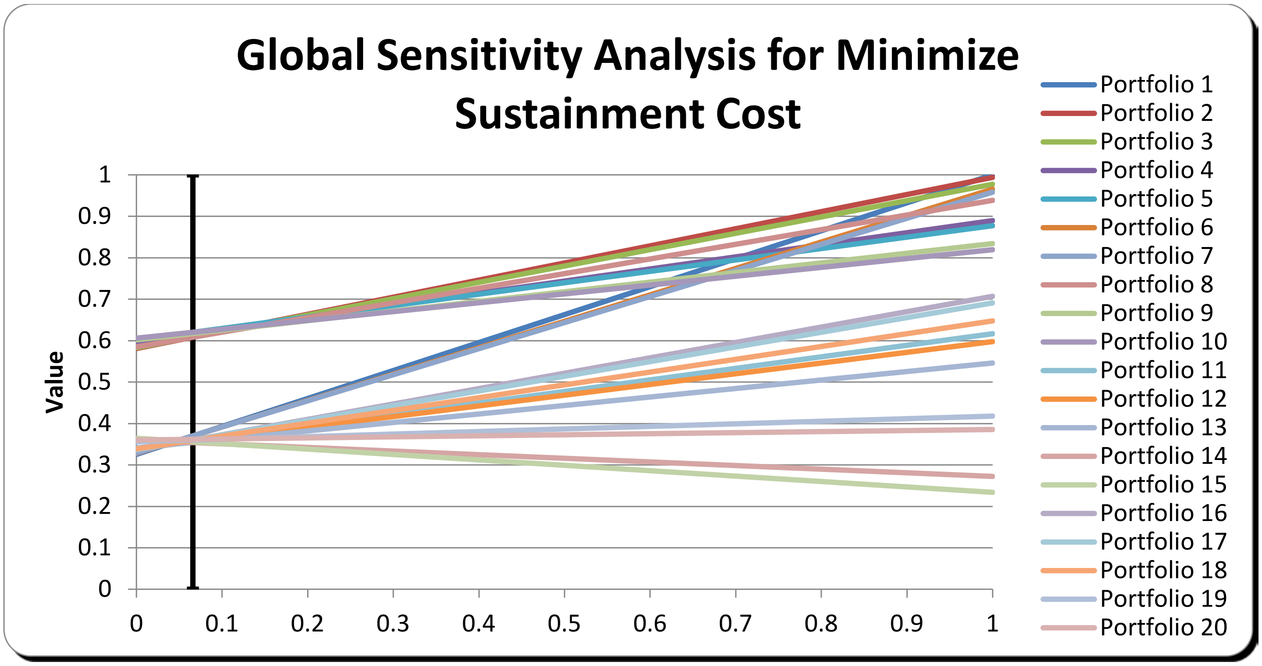
ii. Maximize Deterrence Capability



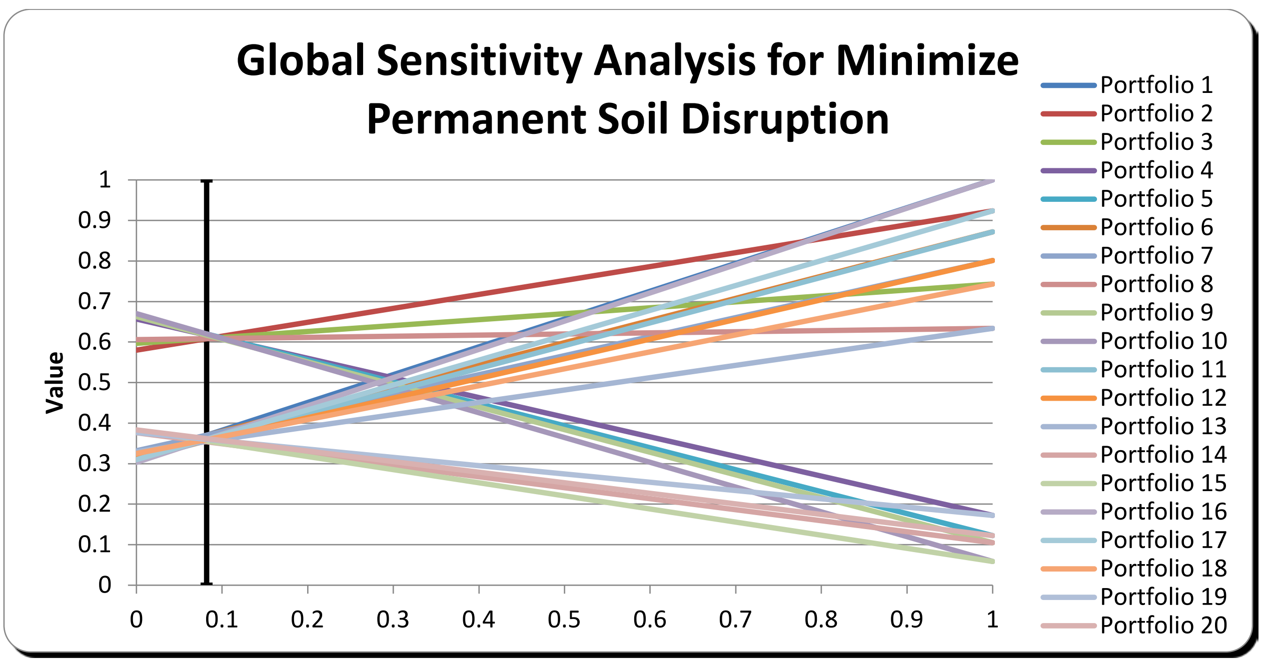
iii. Minimize Acquisition Cost



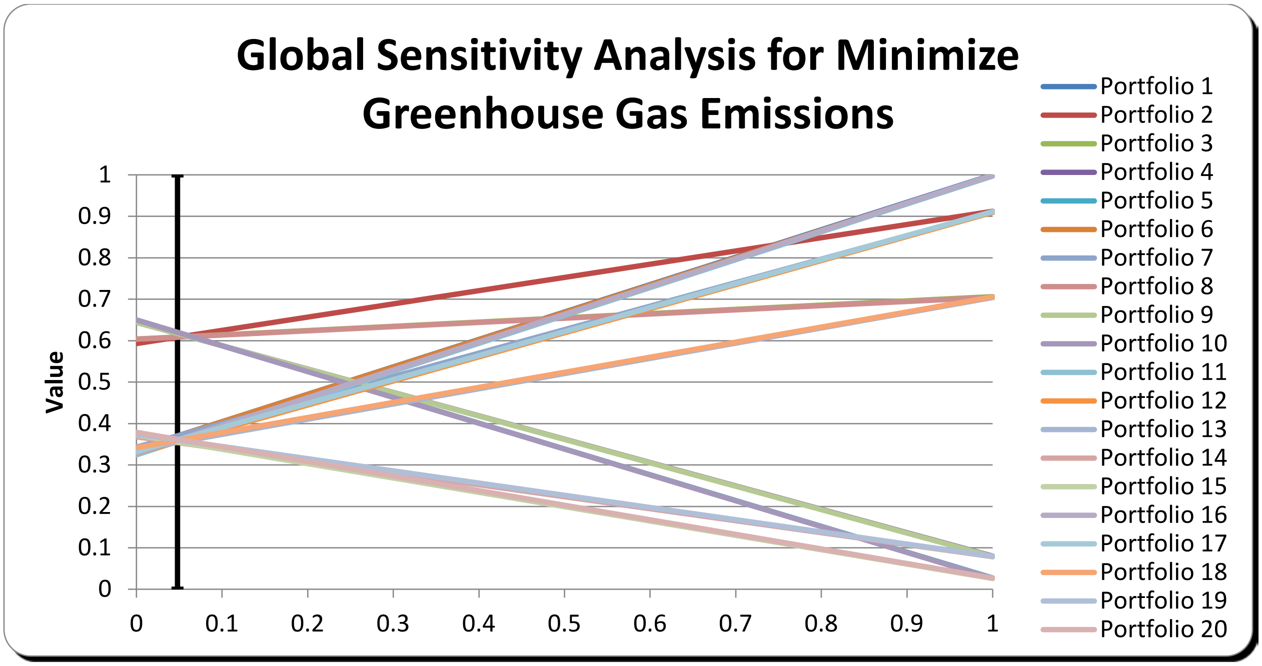
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



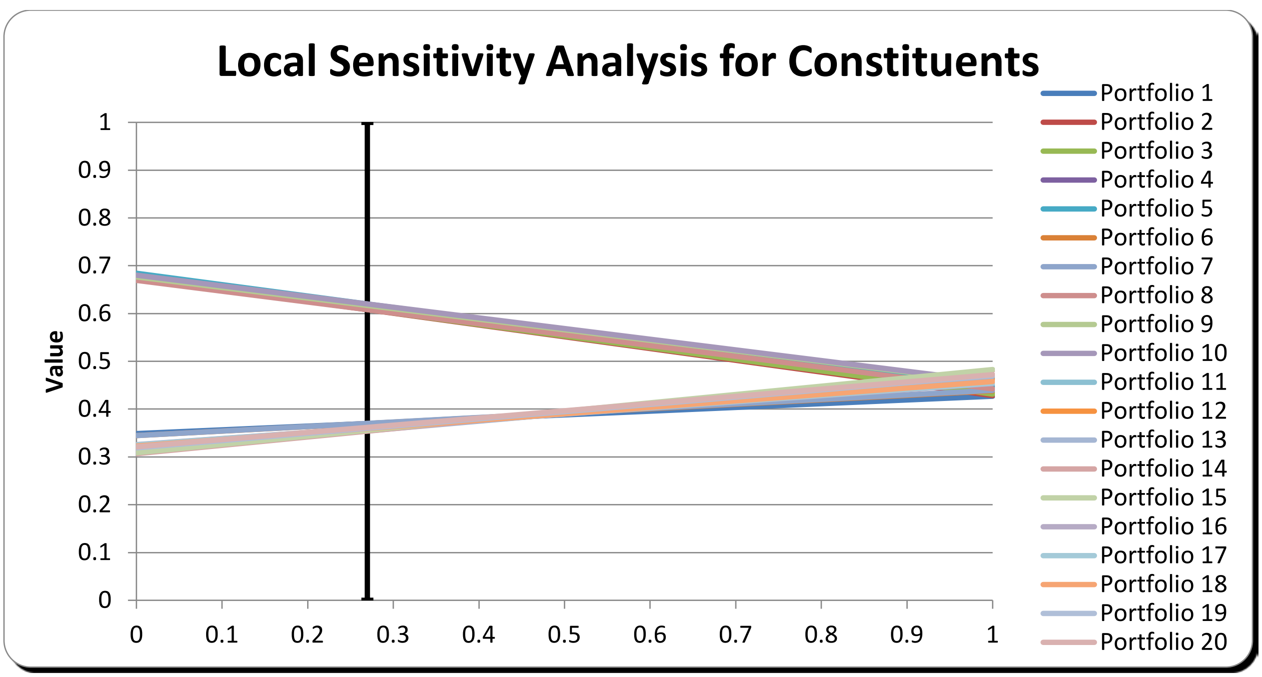
vi. Minimize Greenhouse Gas Emissions



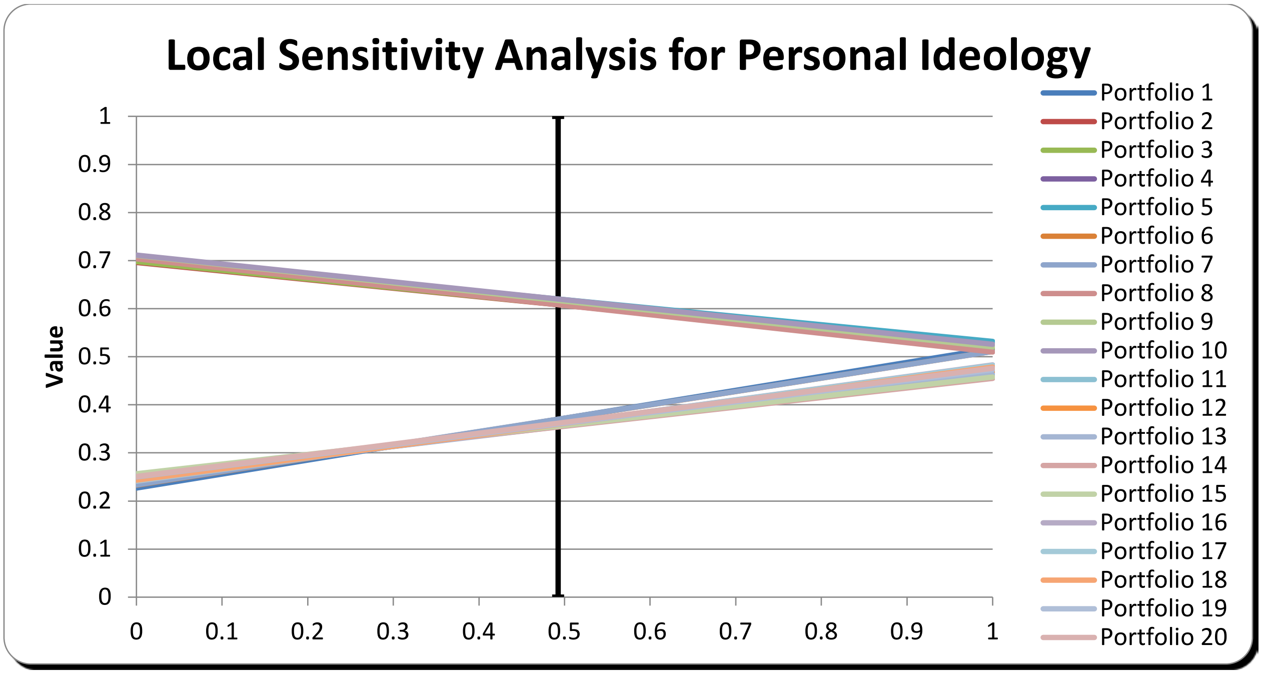
18. Gold Party DM # 8

a. Local Sensitivity Graphs

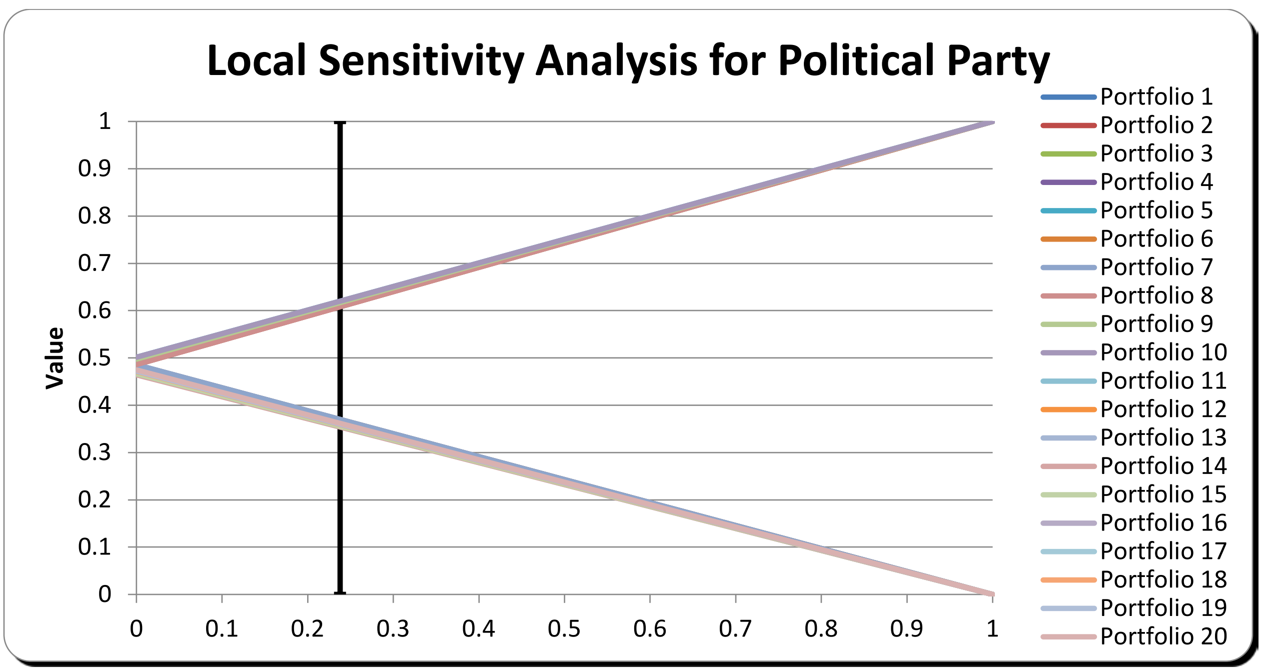
i. Constituent Satisfaction



ii. Personal Ideology

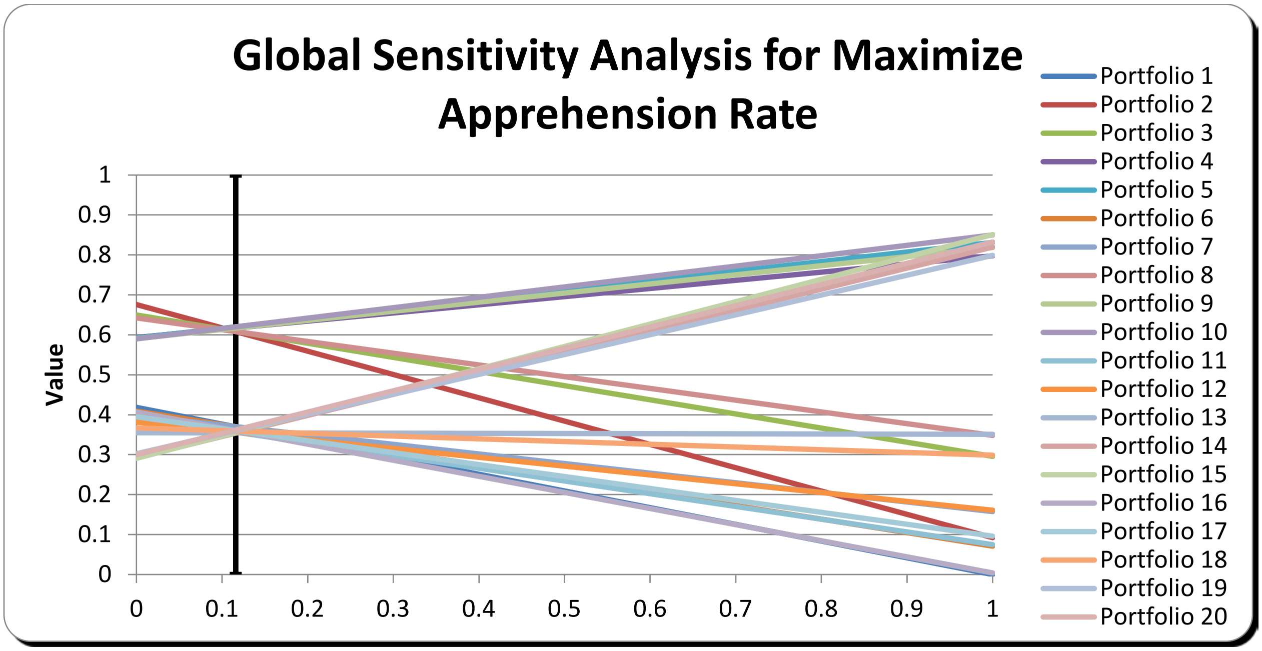


iii. Party Leader Support

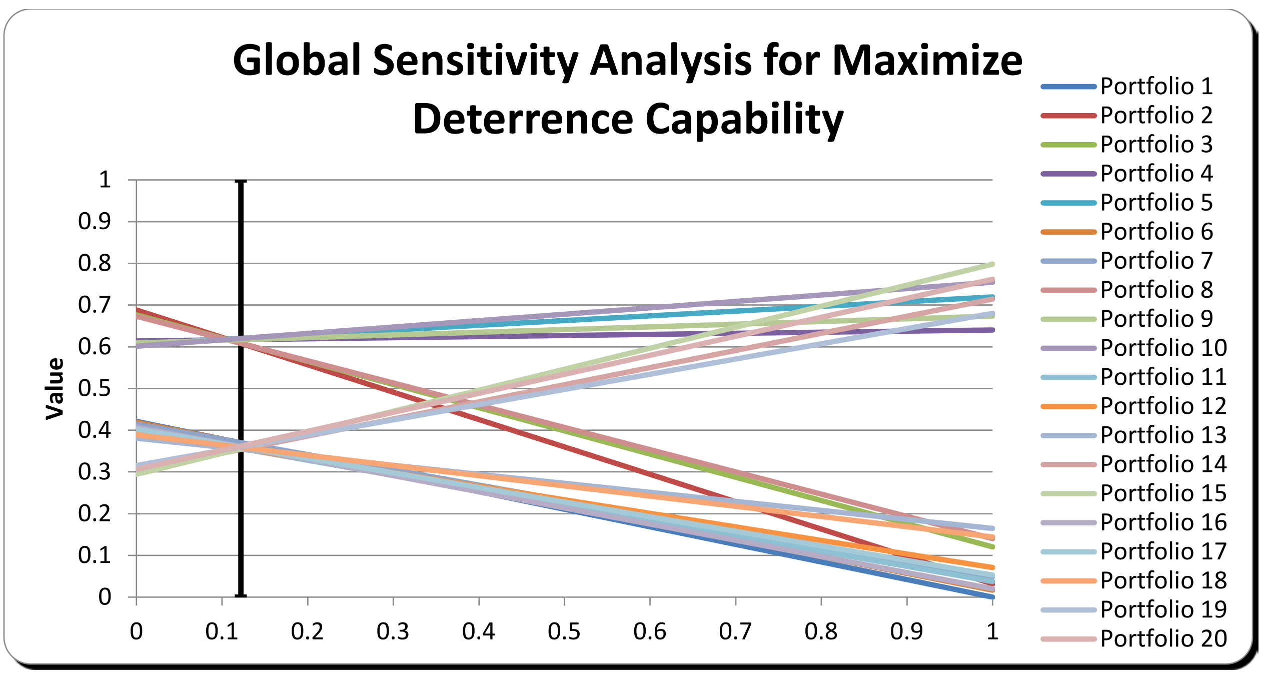


b. Global Sensitivity Graphs

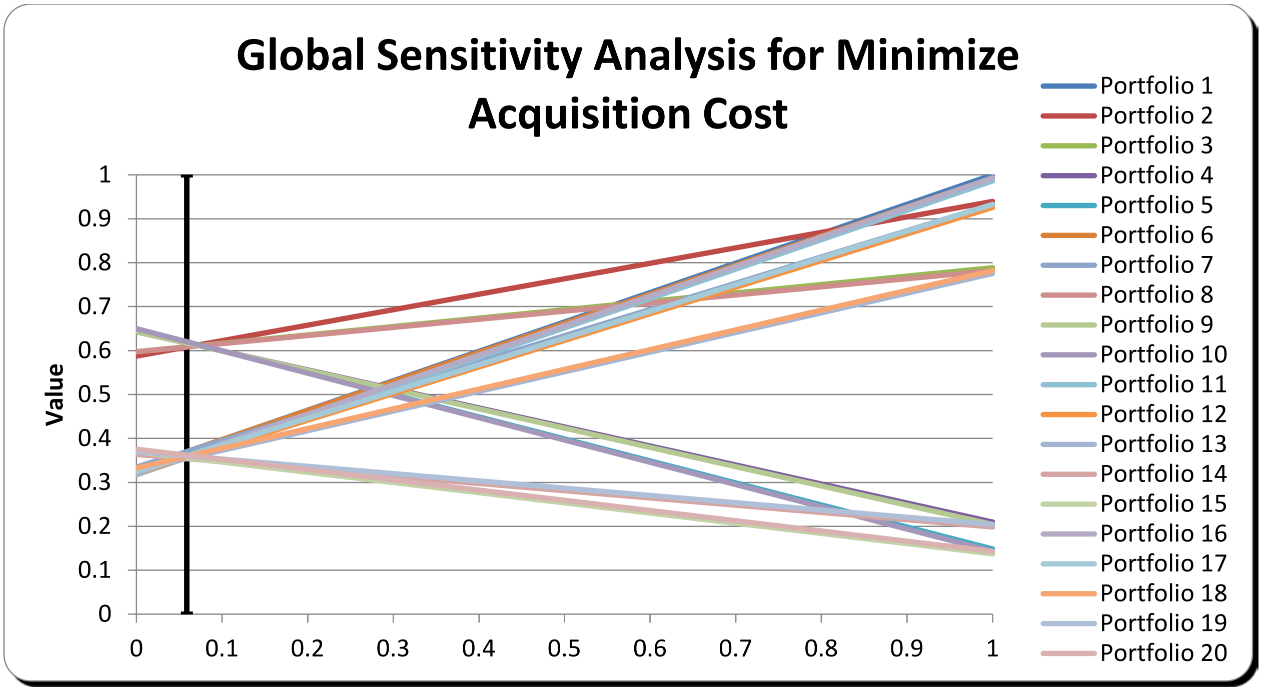
i. Maximize Apprehension Capability



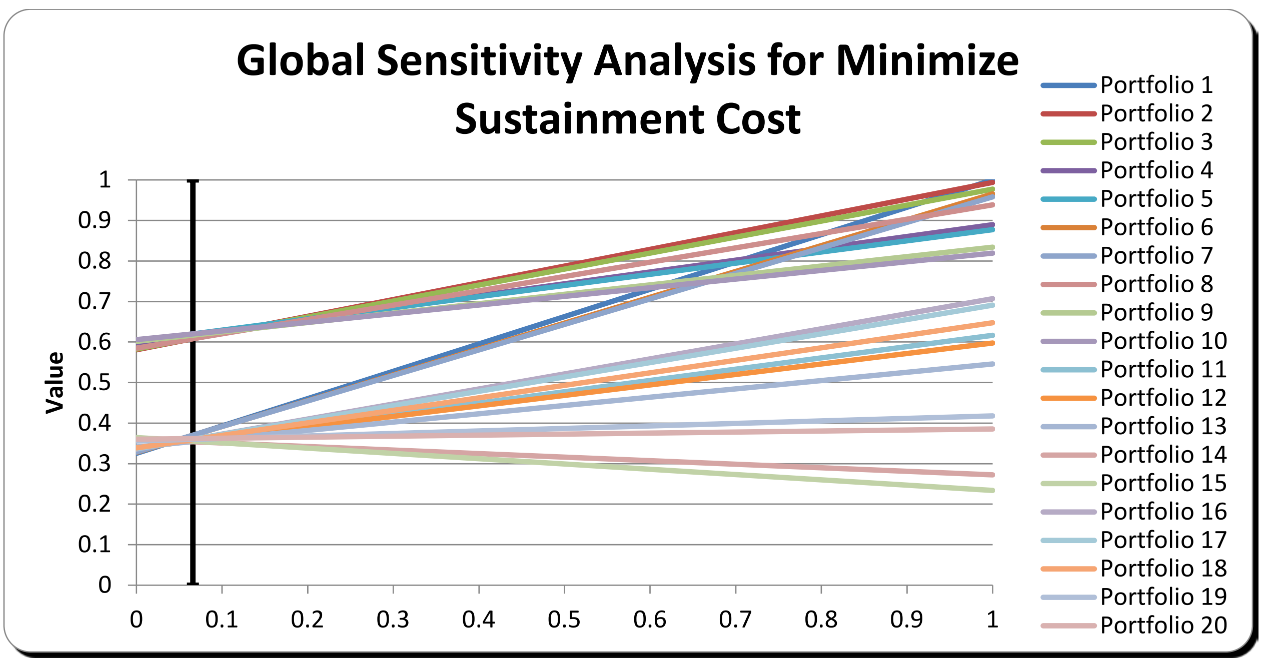
ii. Maximize Deterrence Capability



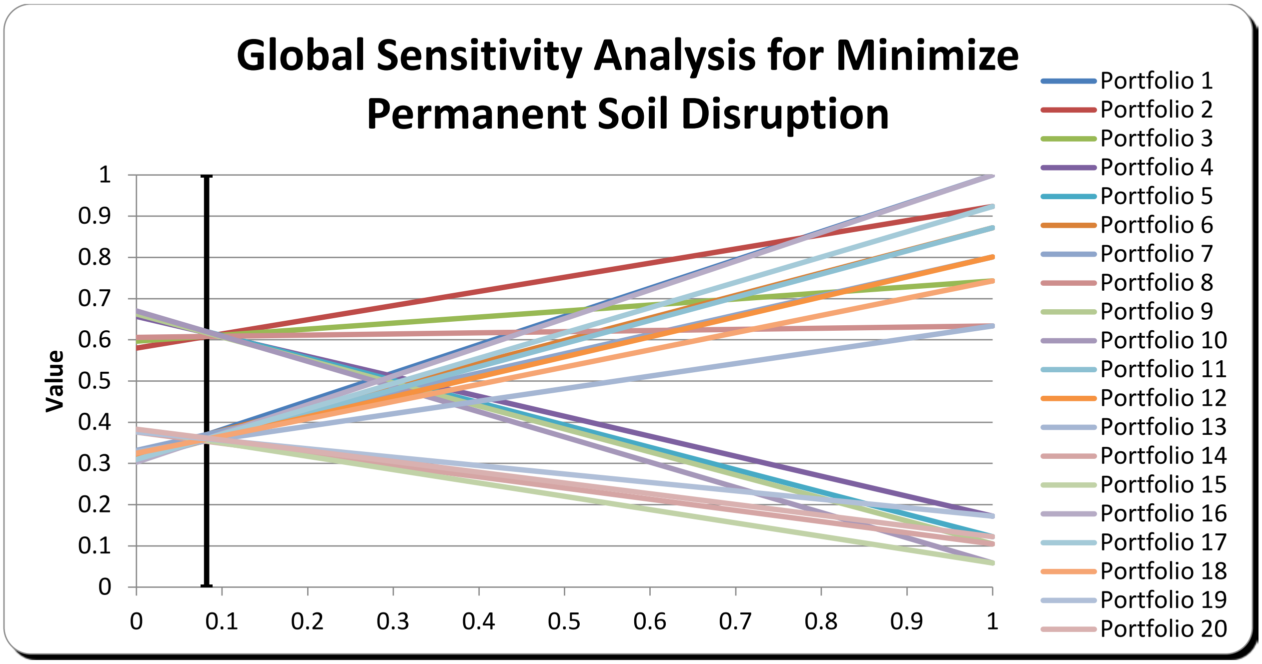
iii. Minimize Acquisition Cost



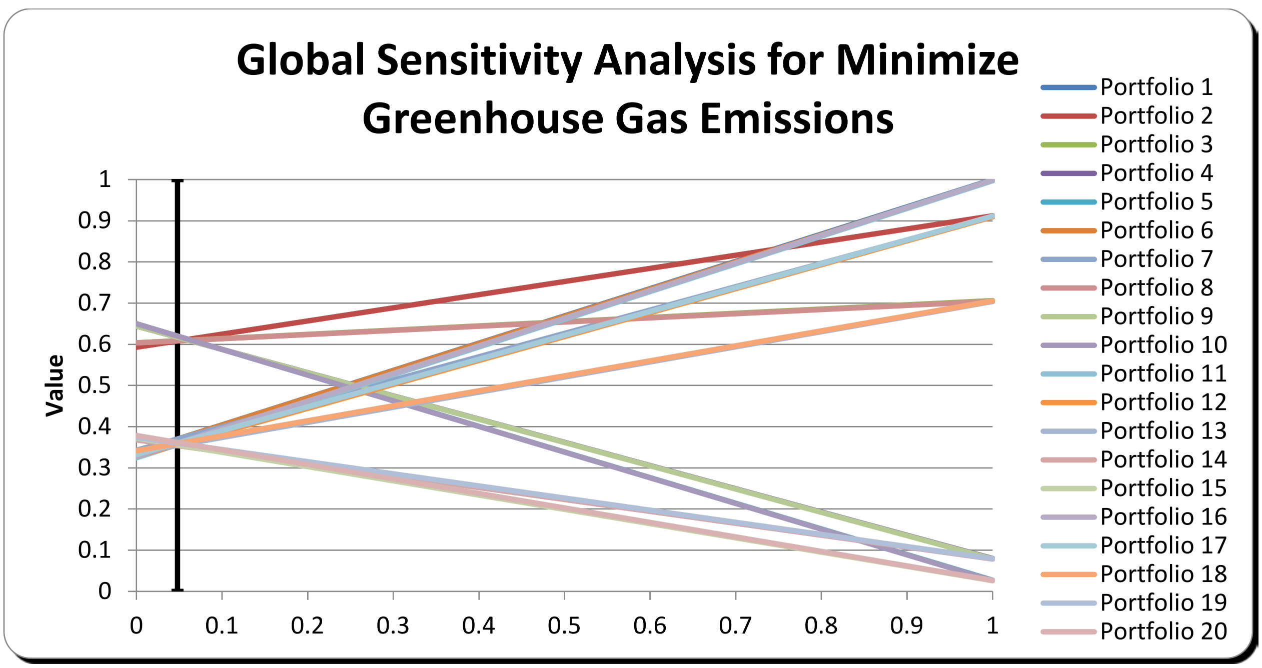
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



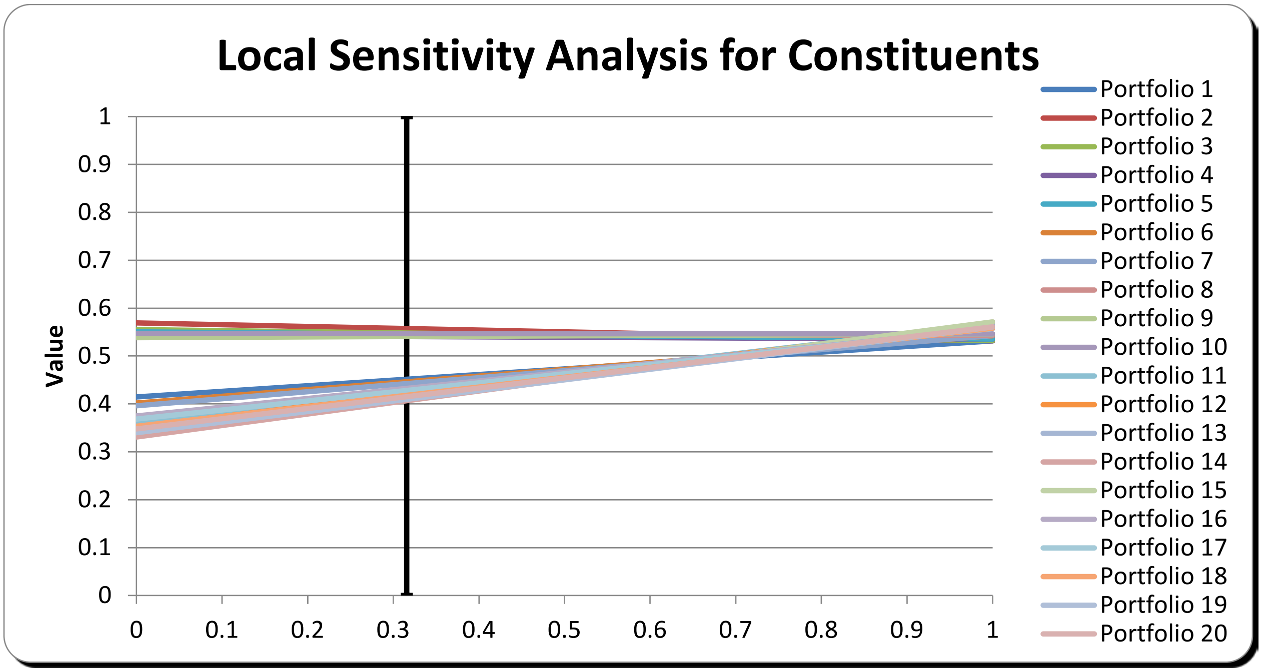
vi. Minimize Greenhouse Gas Emissions



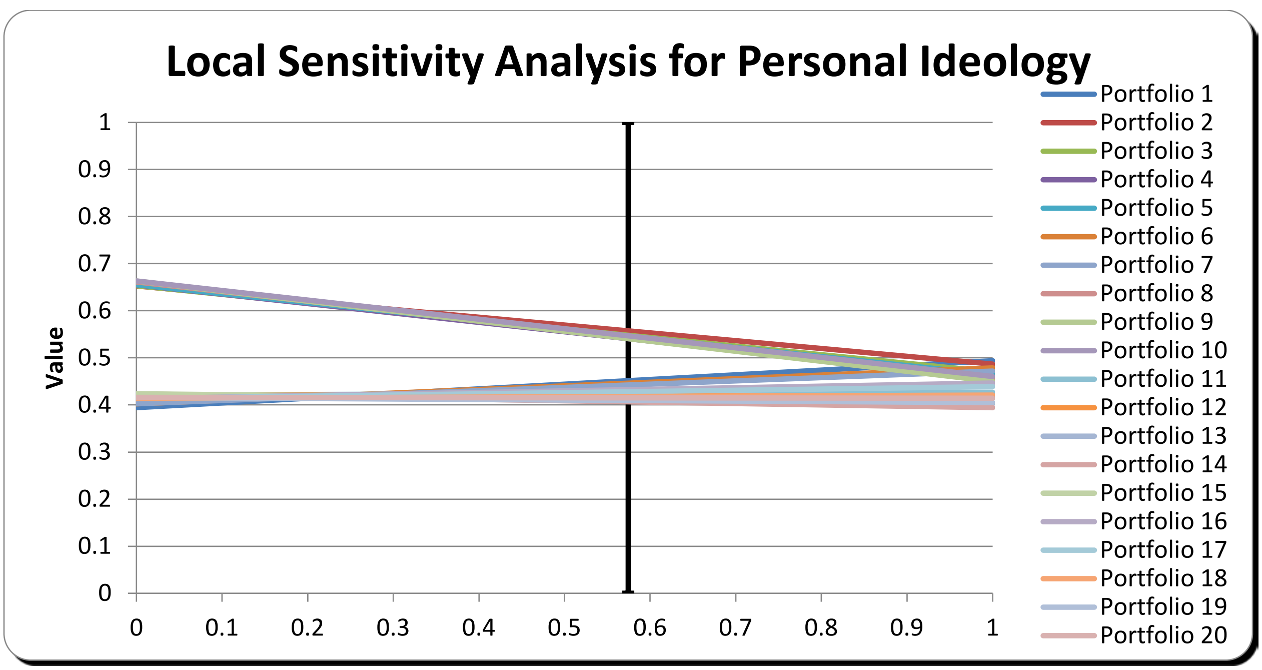
19. Gold Party DM # 9

a. Local Sensitivity Graphs

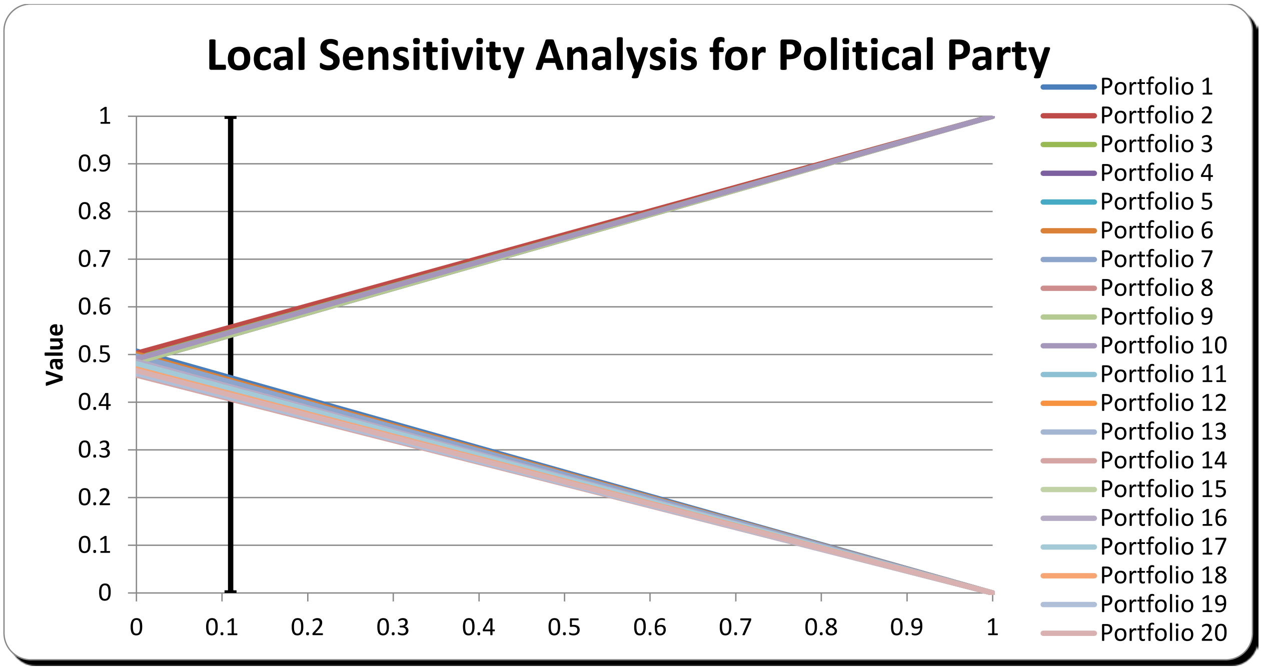
i. Constituent Satisfaction



ii. Personal Ideology

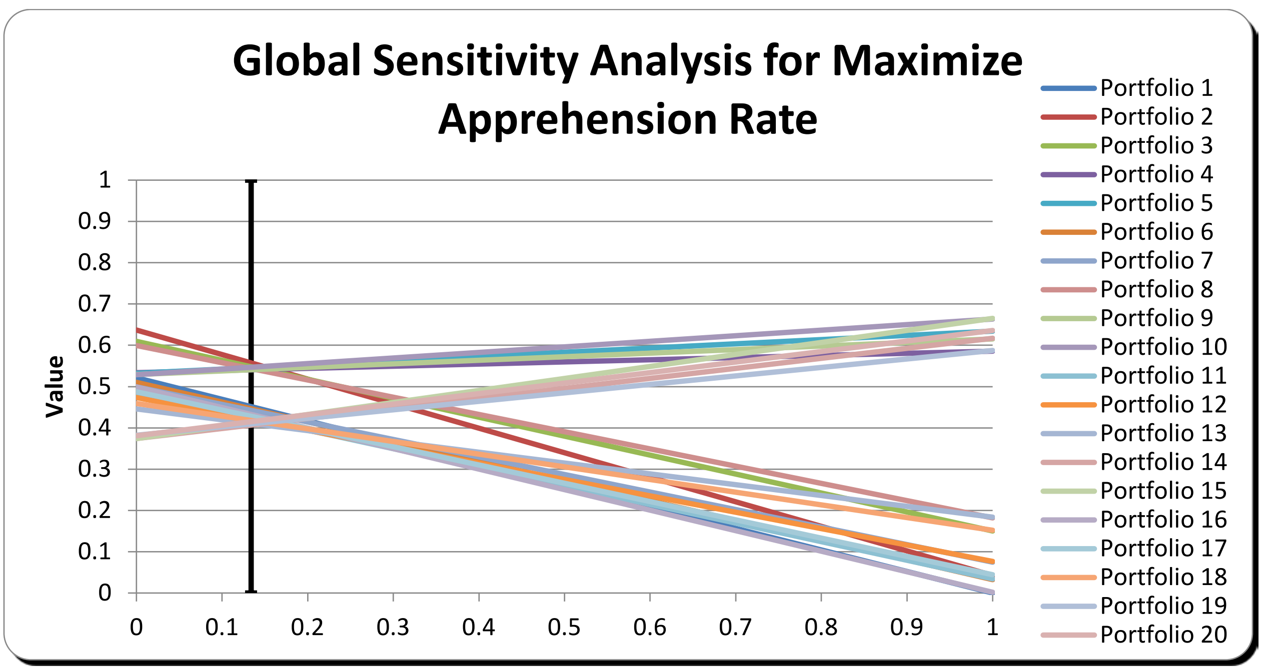


iii. Party Leader Support

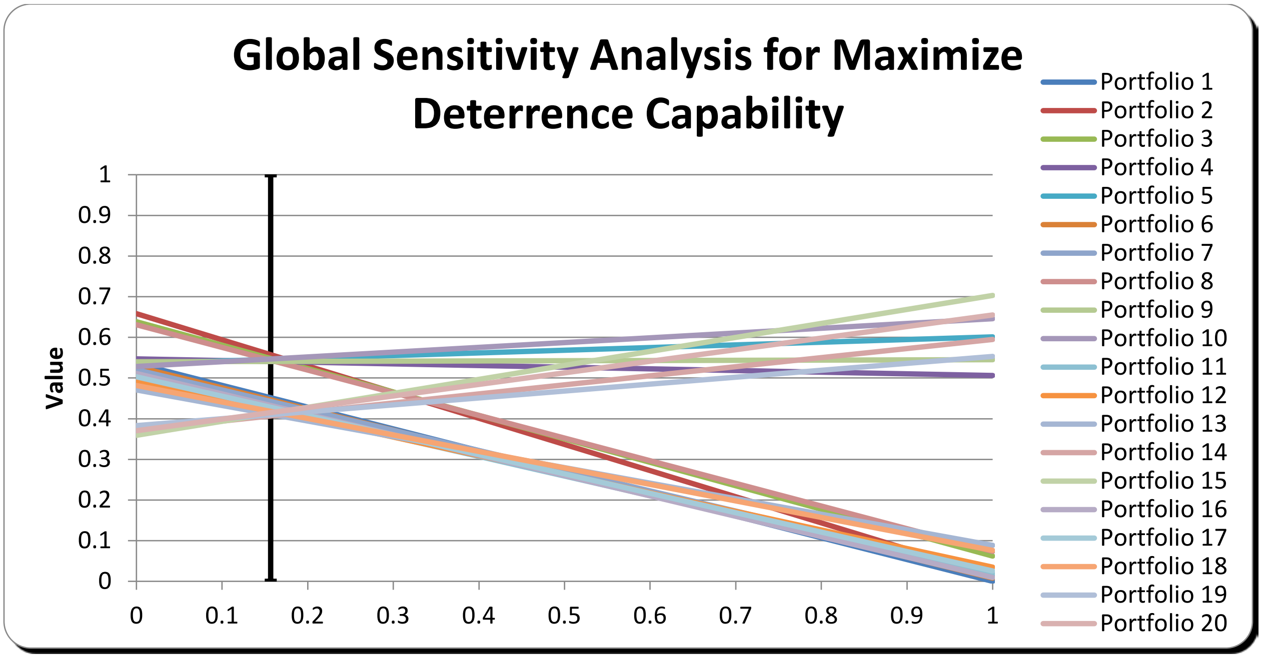


b. Global Sensitivity Graphs

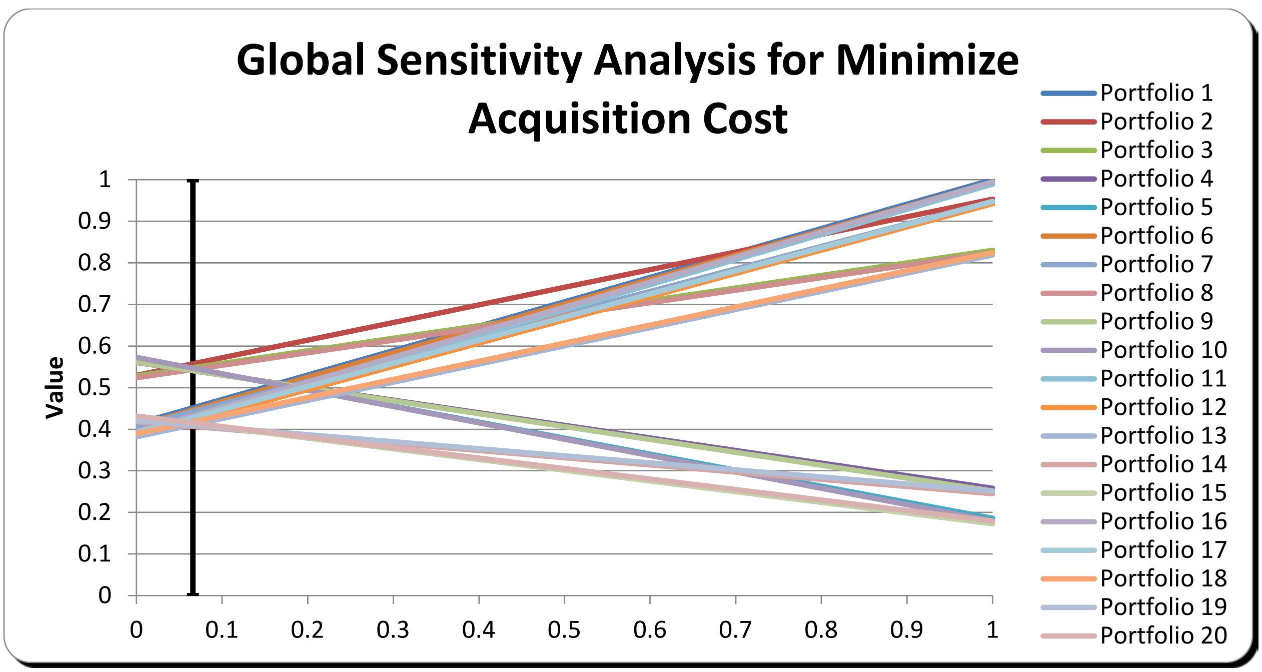
i. Maximize Apprehension Capability



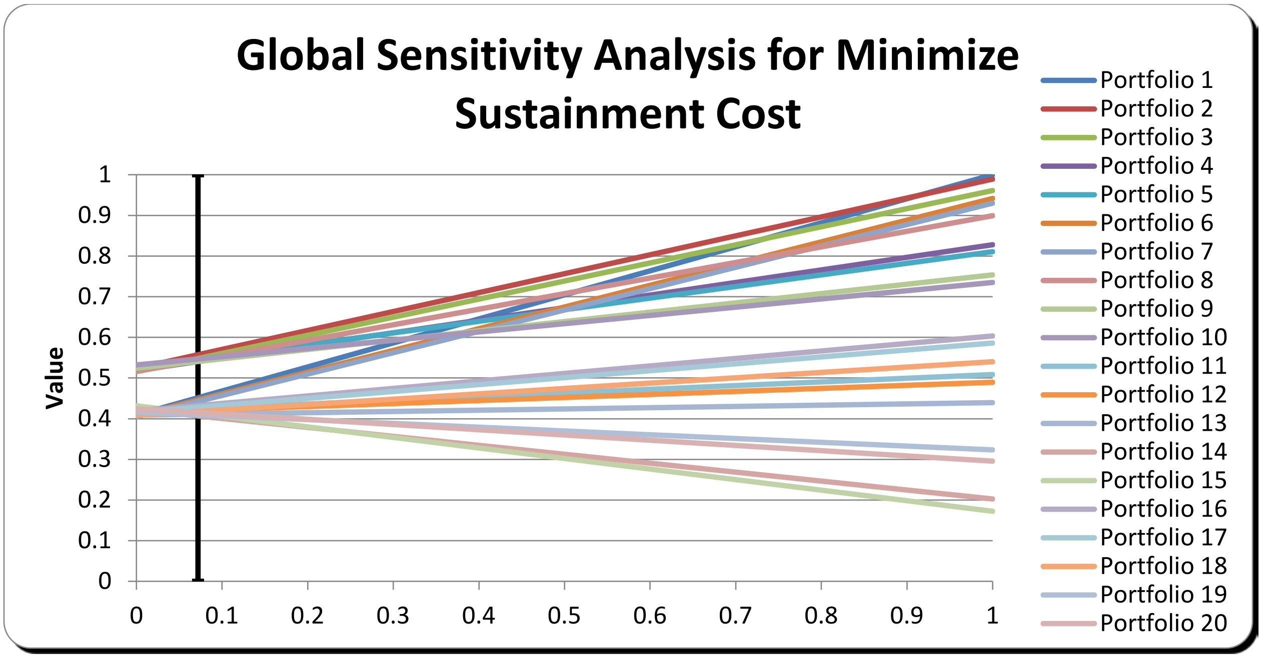
ii. Maximize Deterrence Capability



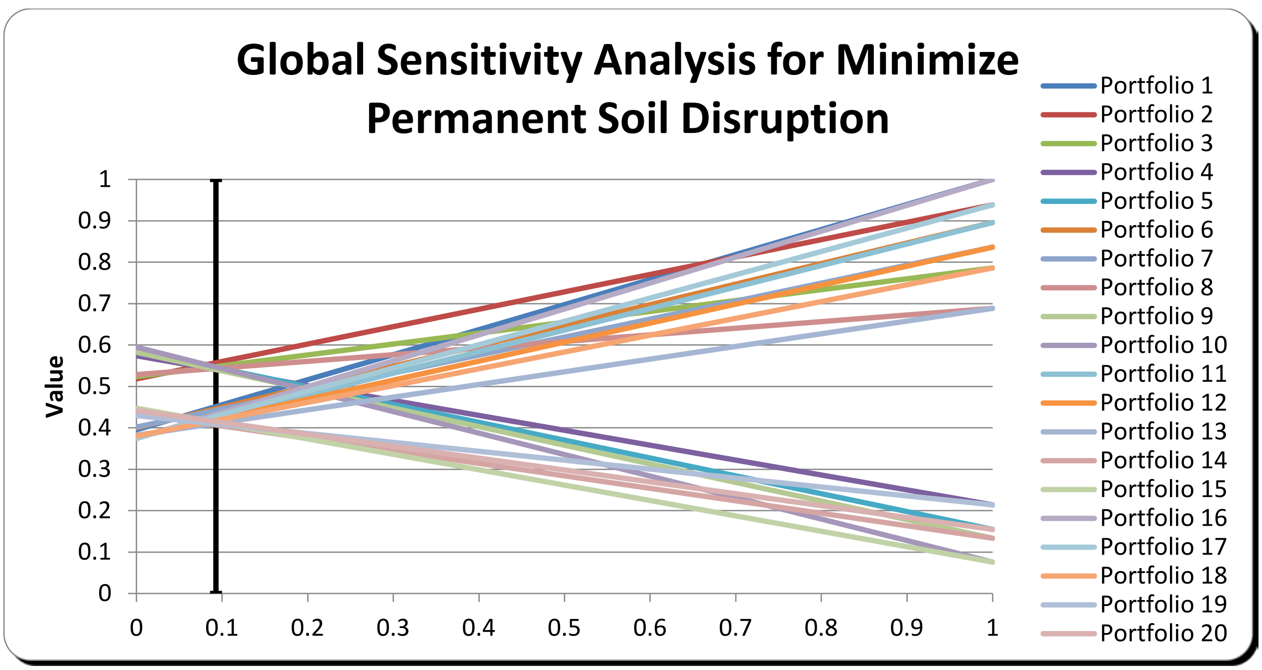
iii. Minimize Acquisition Cost



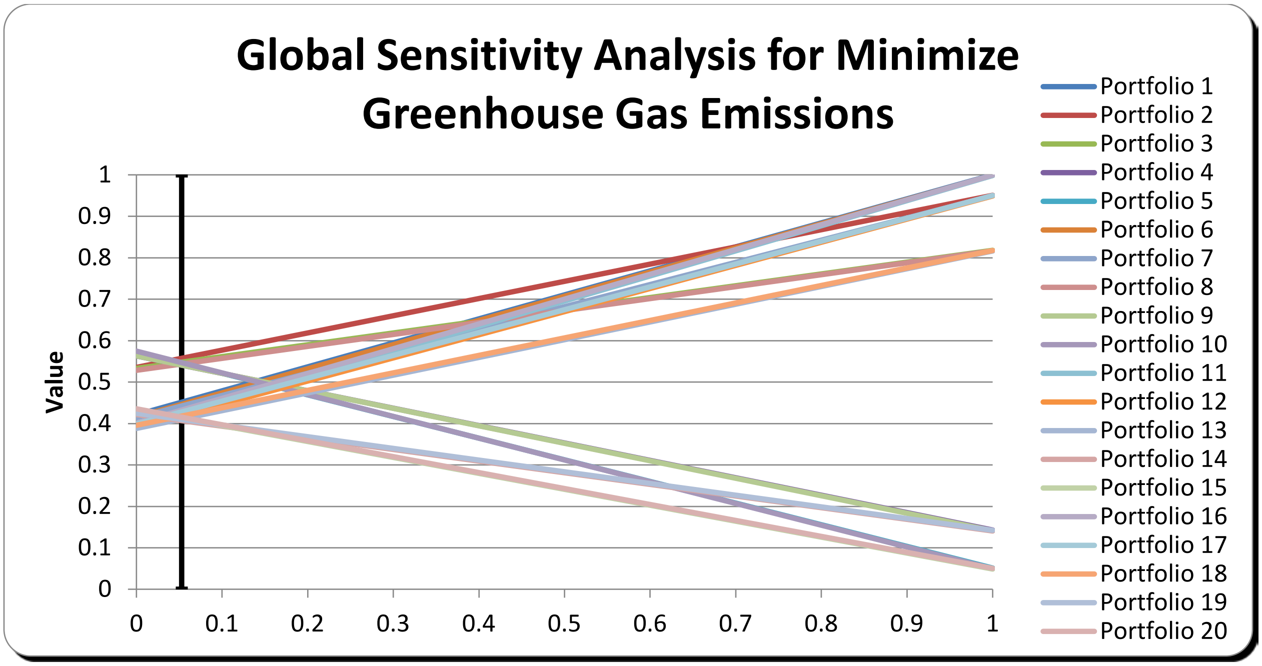
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



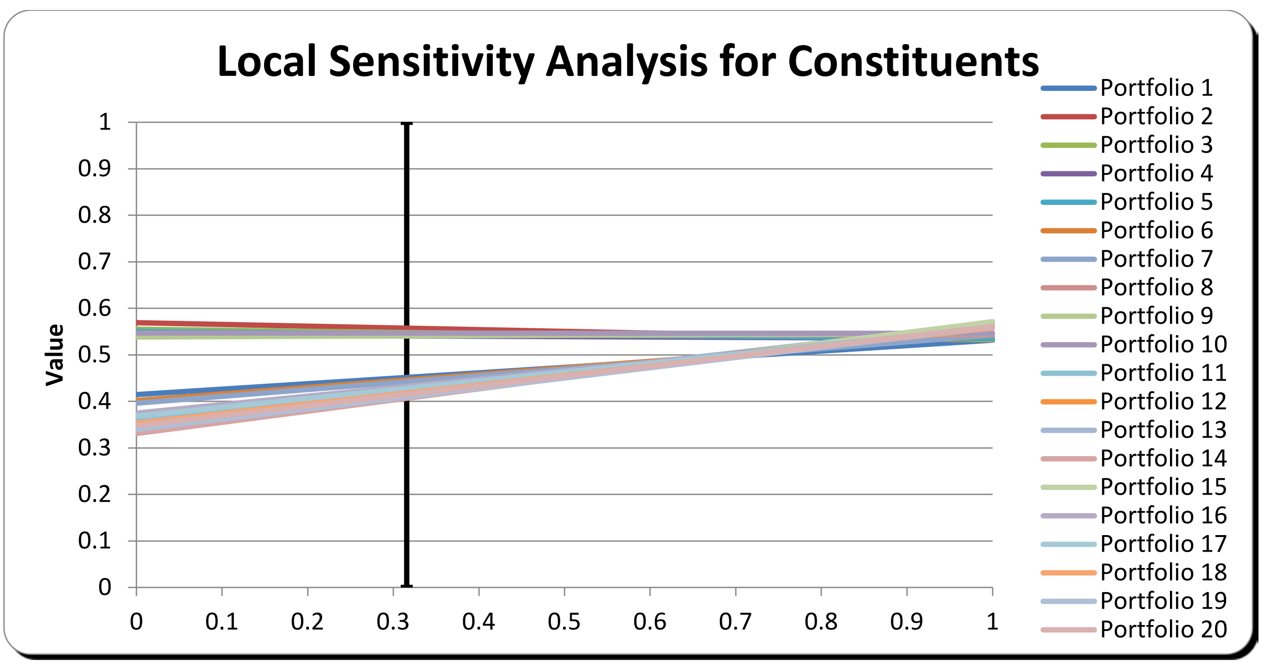
vi. Minimize Greenhouse Gas Emissions



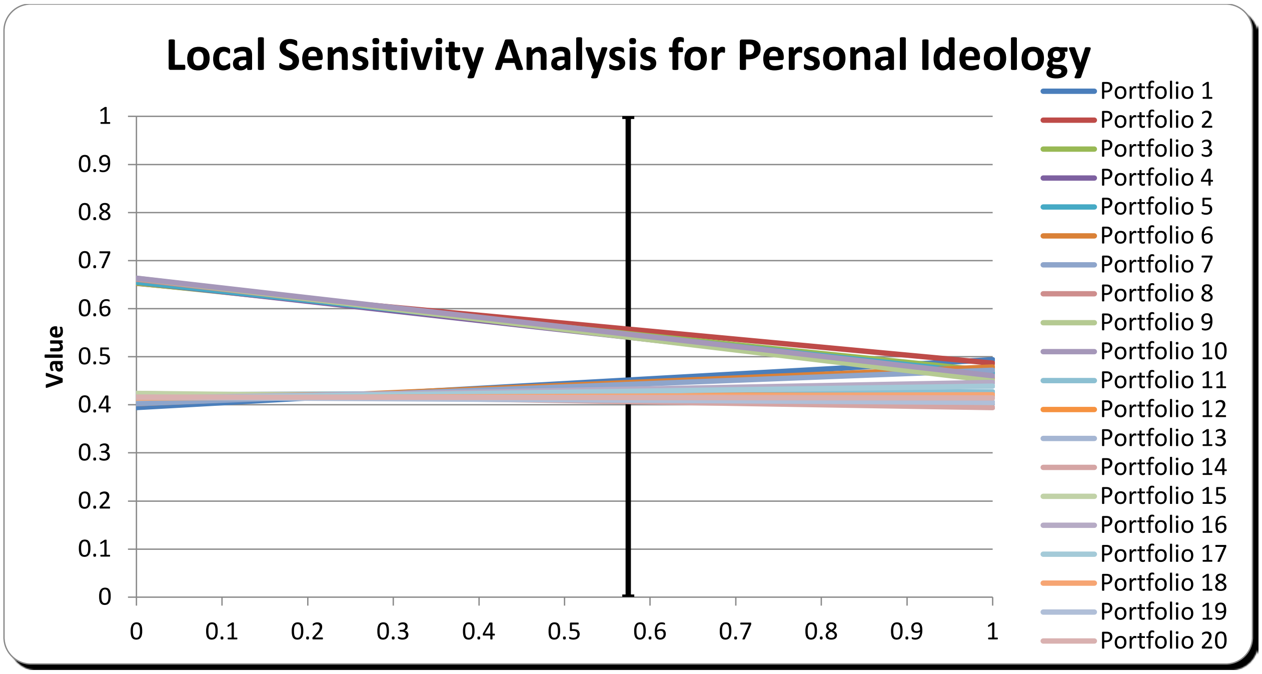
20. Gold Party DM # 10

a. Local Sensitivity Graphs

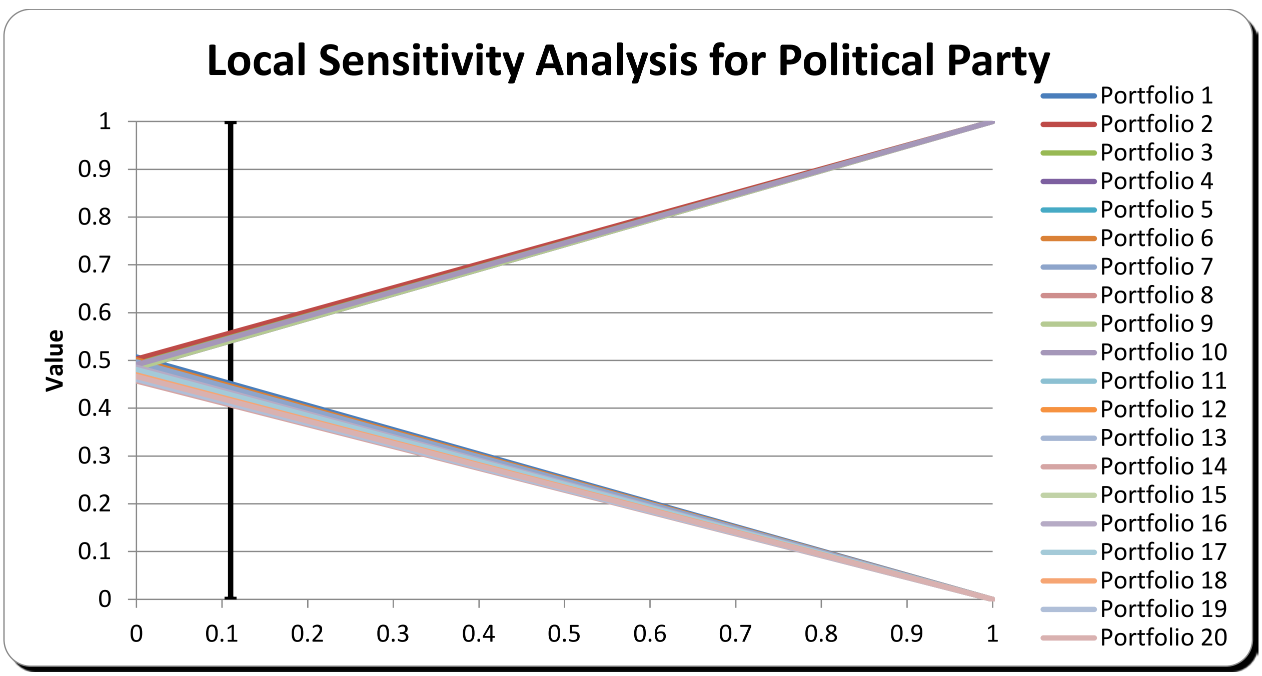
i. Constituent Satisfaction



ii. Personal Ideology

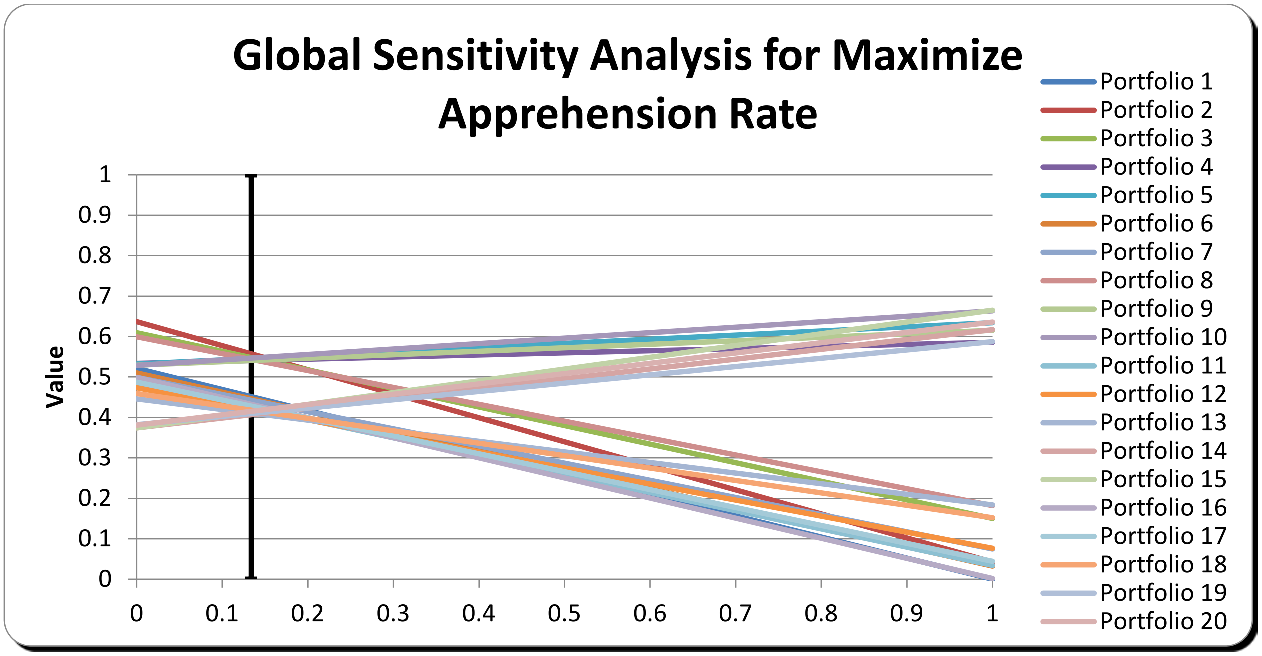


iii. Party Leader Support

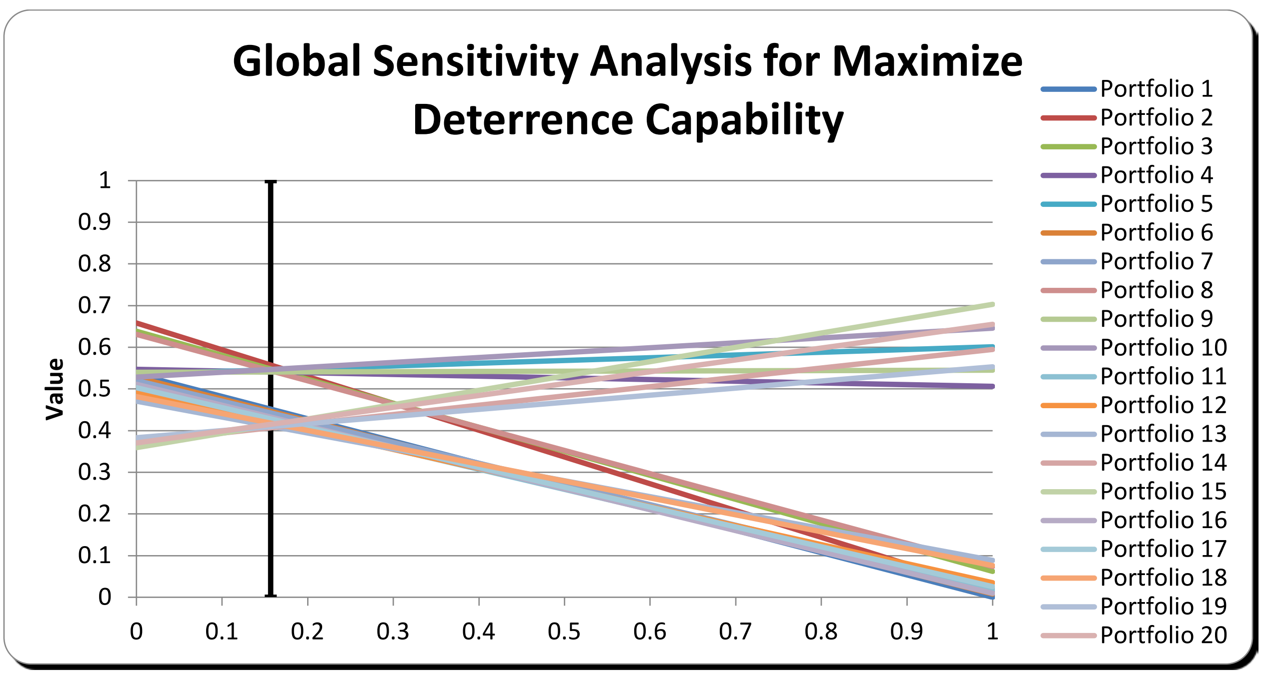


b. Global Sensitivity Graphs

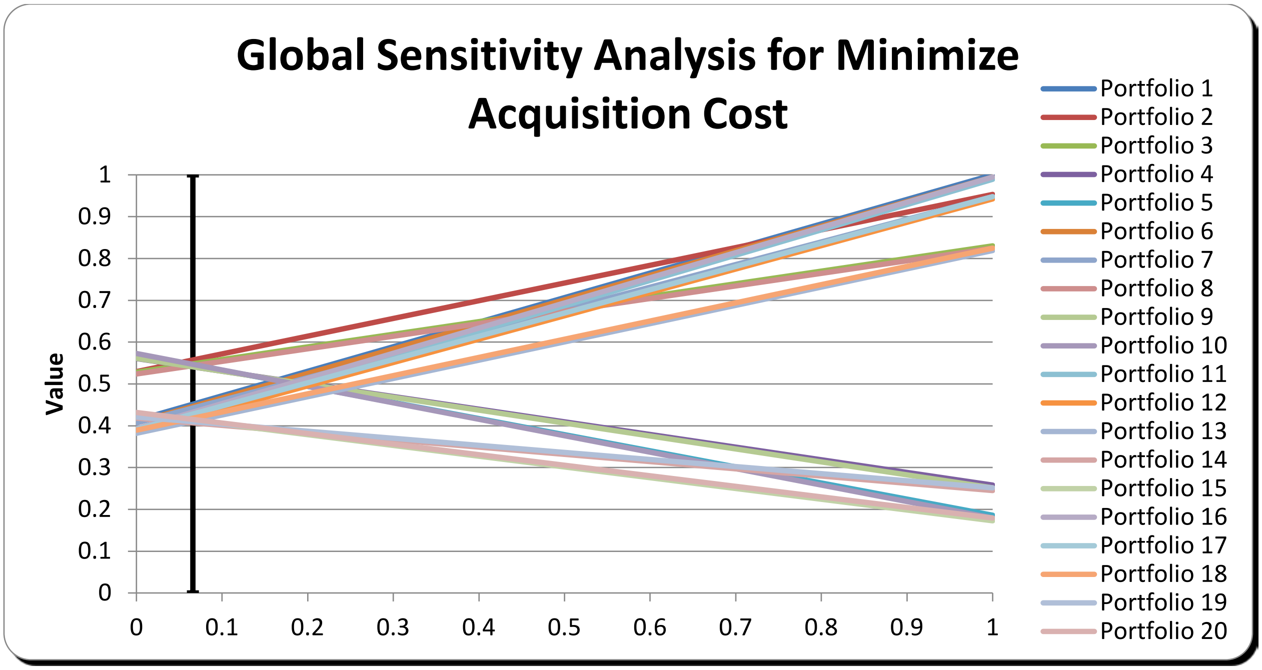
i. Maximize Apprehension Capability



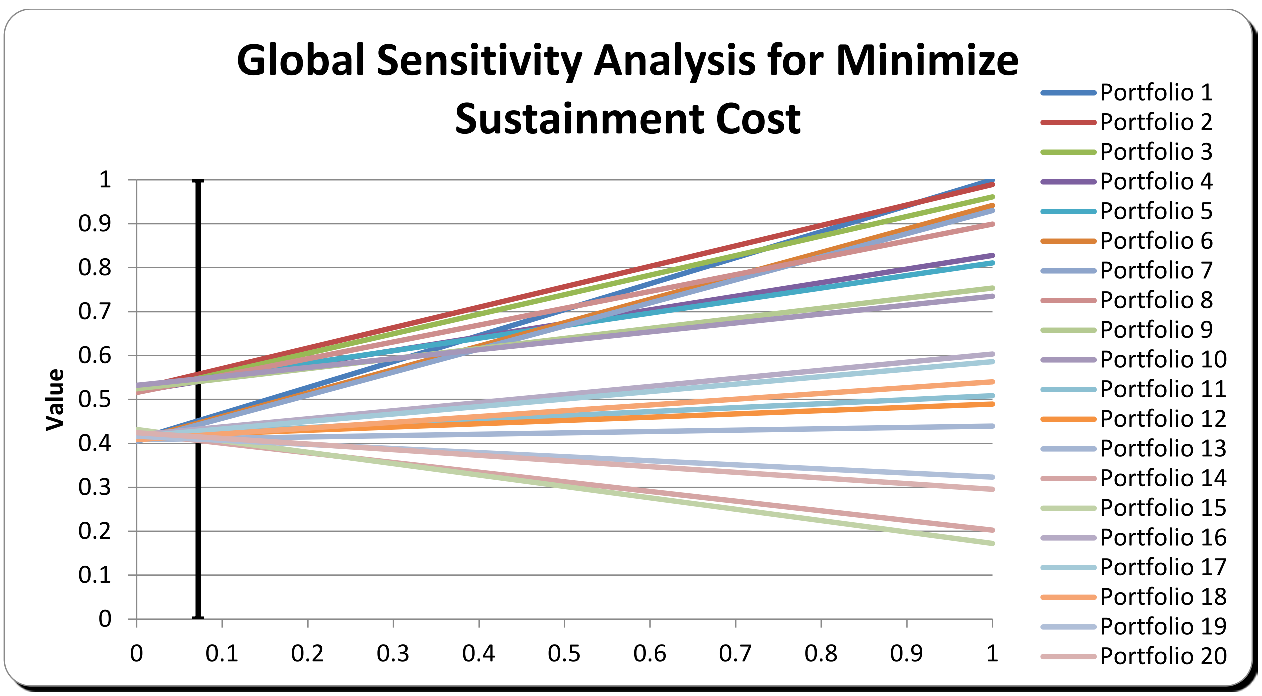
ii. Maximize Deterrence Capability



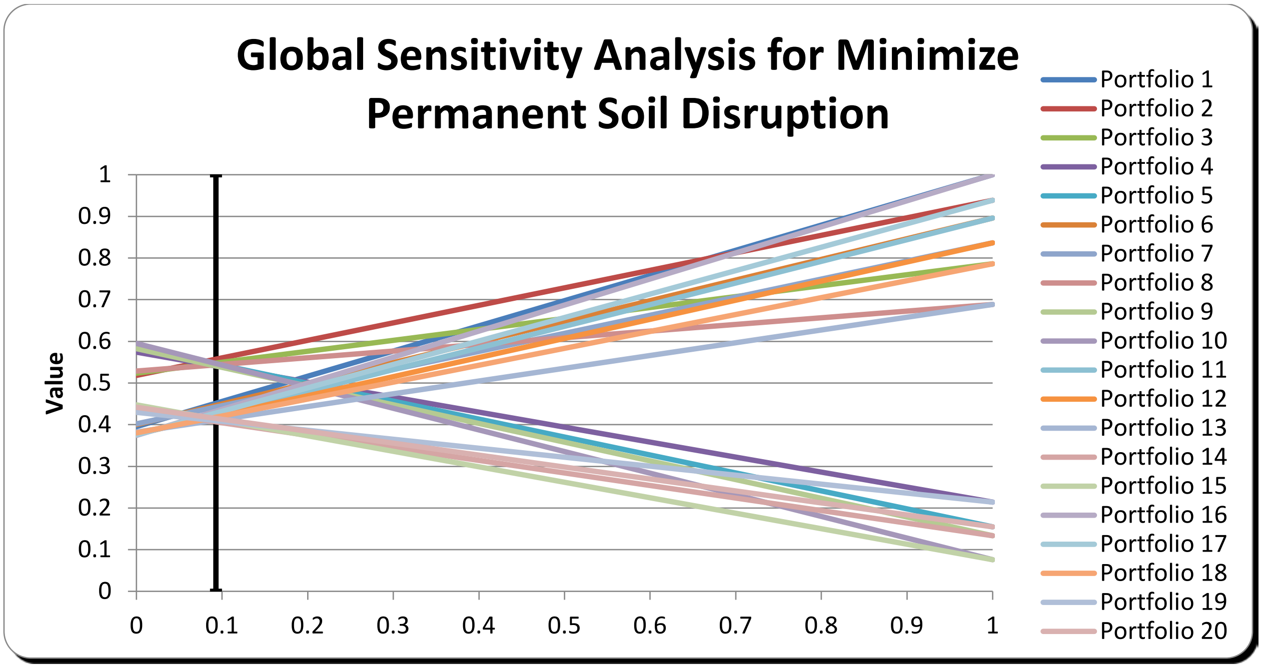
iii. Minimize Acquisition Cost



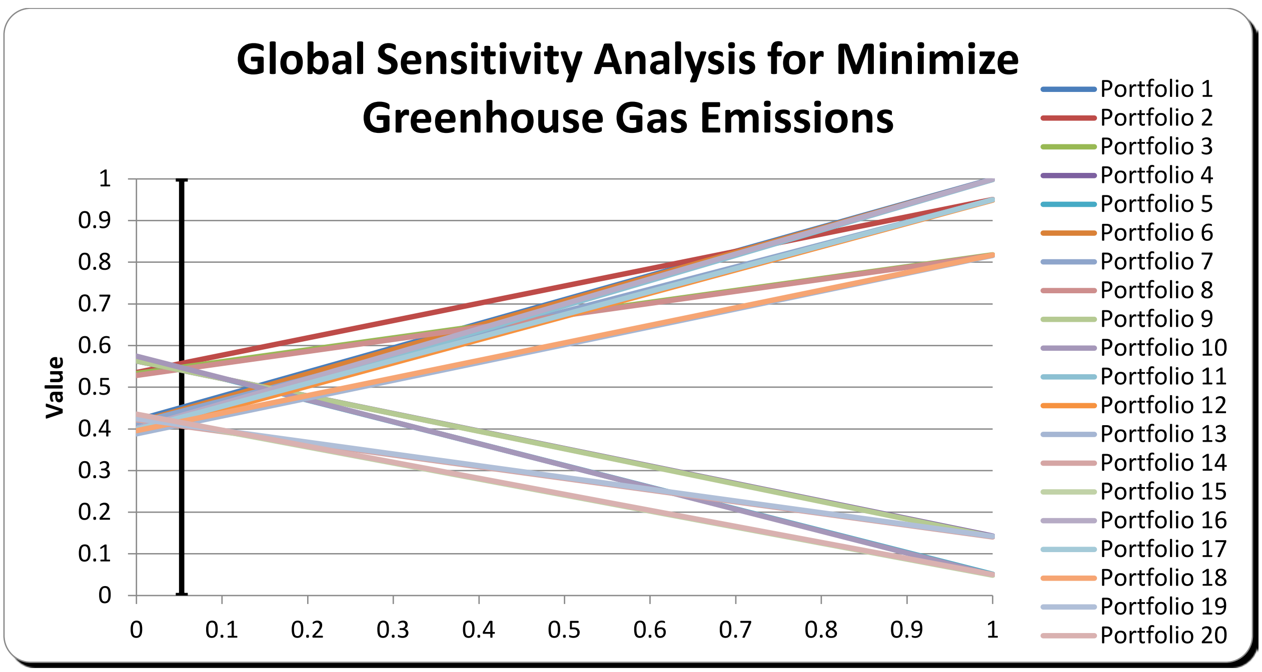
iv. Minimize Sustainment Cost



v. Minimize Permanent Soil Disruption



vi. Minimize Greenhouse Gas Emissions



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14. ABSTRACT

In December 2018, the U.S. Government began the longest government shutdown in U.S. history. These shutdowns occur after government departments submit budget requests and the legislature is unable to pass an appropriations bill. There is no clear solution to this problem. This study hypothesizes that government departments could benefit from considering the political viability of their budget requests prior to submitting them to Congress. In the field of decision analysis, no prior research was found for assessing the political viability of alternatives. This work theorizes and tests a novel methodology for vote forecasting using the results of a multi-objective decision analysis and comparing alternatives against the status quo. A model scenario is set forth of Customs and Border Protection submitting a funding request for technologies to secure the United States-Mexico border. The request is sent to a voting body of 20 decision makers from 2 political parties. A total of 20 alternatives are assessed according to the individual preferences of 20 decision makers and votes are forecasted using the results. The experiment made a clear distinction between alternatives with varying levels of political viability. The study contributes a repeatable methodology that can be used for future research in real-life scenarios.

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