ENVIRONMENTAL DECISION MAKING USING MULTIPLE PARTICIPANT-MULTIPLE CRITERIA DECISION TECHNIQUES

By

Monika Karnis

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Environmental Decision Making Using Multiple Participant-Multiple Criteria Decision Techniques

Master of Applied Science, 2015

Monika Karnis

Mechanical and Industrial Engineering

Ryerson University

Abstract

Two environmental decision making problems are investigated utilizing decision making methods found to be appropriate for each situation. The first study on sustainability alternatives for the aviation industry evaluates possible actions by the industry in order to reduce emissions by utilizing multiple criteria decision making methods. Interdependence of alternatives is considered. In the second study, the graph model for conflict resolution is utilized to investigate the controversy surrounding the recommendations by the International Joint Commission on the fluctuating water levels in the Laurentian Great Lakes. These studies are carried out to clarify and understand the values and considerations that have led to the participants' decision making behavior so that insights on creating movement towards desired outcomes are revealed. If the solution is undesirable, the movements on preferences of some participants needed to shift to a better outcome are explored, which add value to the analysis.

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Chapter 1. Introduction

1.1 Background

When a decision problem arises, the perceived solution is selected from a set of possible alternatives (Saaty, 2008). However, the problem and the proposed set of alternatives exist in an environment that is defined by its set of circumstances and conditions that affect the manner in which the problem can be solved (Hipel et al., 1993). The environment can be defined by four major factors (Hipel et al., 1993):

1. Whether uncertainty exists in the decision being considered,
2. Whether the costs and benefits from implementing one of the alternatives can be described in quantitative or qualitative terms,
3. If the decision problem has single or multiple objectives, and
4. Whether the power to make the decision lies with one individual or more than one participant.

These factors define the type of decision making situation; whether the problem is a single participant-single criterion decision, a single participant–multiple criteria decision, a multiple participant–single criterion decision, or a multiple participant–multiple criteria decision problem (Radford et al., 1994). The simplest combination of these factors is where the alternatives can be evaluated in a quantitative way and when there is a single participant with a single objective. It is simple because there is no uncertainty in the outcome; a decision maker must make a choice between alternatives based on an evaluation of those alternatives in a quantitative form (Hipel et al., 1993). Examples of this type of decision problem can be found in routine operational processes, like the selection of a material vendor based on price and barring any other criteria (Hipel et al., 1993). A decision problem becomes more complex when it has an uncertain outcome, the alternatives can be measured in a qualitative or quantitative way, whether it has single or multiple objectives, and whether it has one or more decision maker. These possibilities can be broken down into three distinct scenarios, which have uncertain outcomes that can be described quantitatively or qualitatively, the difference between them is how many decision makers and criteria they have. However, if a decision maker expresses uncertainty with its preferences then a sensitivity analysis or a fuzzy set-based method can be used to determine the robustness of the solution (Van Laarhoven and Pedrycz, 1983).

The first scenario is described as uncertain with quantitative or qualitative outcomes, one decision maker and multiple objectives. This situation is referred to as a single participant-multiple criteria (SPMC) decision problem (Radford et al., 1994). In this problem, discrete alternatives are evaluated against different criteria in order to rank the alternatives (Hipel et al., 1993). In the literature, single participant-multiple criteria decision problems are often referred to as multiple criteria decision making (MCDM) or multiple objective decision making (MODM) problems (Keeney and Raiffa, 1976; Saaty, 1980; Hobbs and Meier, 2000).

In this structure, the alternatives are evaluated separately from each criterion. A criterion is said to be quantitative when cardinal numbers are used to represent a decision maker's preferences for the alternatives with respect to the criterion (Hipel et al., 1993). An example of this would be a criterion for cost, which can be represented as a cardinal utility value like dollars. If a criterion cannot be described quantitatively, like aesthetics, it is called qualitative (Hipel et al., 1993).

Now that SPMC decision problems have been described, the next scenario for consideration is where there are multiple decision makers, each of which has one criterion. The states of a decision situation are determined jointly by possible actions of the decision makers. When states are evaluated by each decision maker using only one criterion of its own, the decision problem is called multiple participant-single criterion (MPSC) decision making (Radford et al., 1994).

The last type of decision problem to be considered is the multiple participant-multiple criteria (MPMC) decision problem, which involves the use of multiple criteria by decision makers for evaluating states (Radford et al., 1994). Each decision maker’s preferences across the states may be different for each set of criteria (Hipel et al., 1993). Each decision maker is faced with a SPMC problem with respect to its own set of criteria as a part of the MPMC problem. Each decision maker is also faced with an MPSC problem with respect to its interactions with the other decision makers (Hipel et al., 1993). If the SPMC problem for each decision maker could be solved, then the interactions between it and the other decision makers would be reduced to a multiple participant-single criterion decision problem, which is shown in Figure 1.1.1. Figure 1.1.1 shows the relationships between the three decision making scenarios discussed in this section. Note that there is a conversion going between MPMC problems to MPSC problems but not vice versa because there is no reasonable way to convert a MPSC situation into a MPMC problem (Radford et al., 1994).

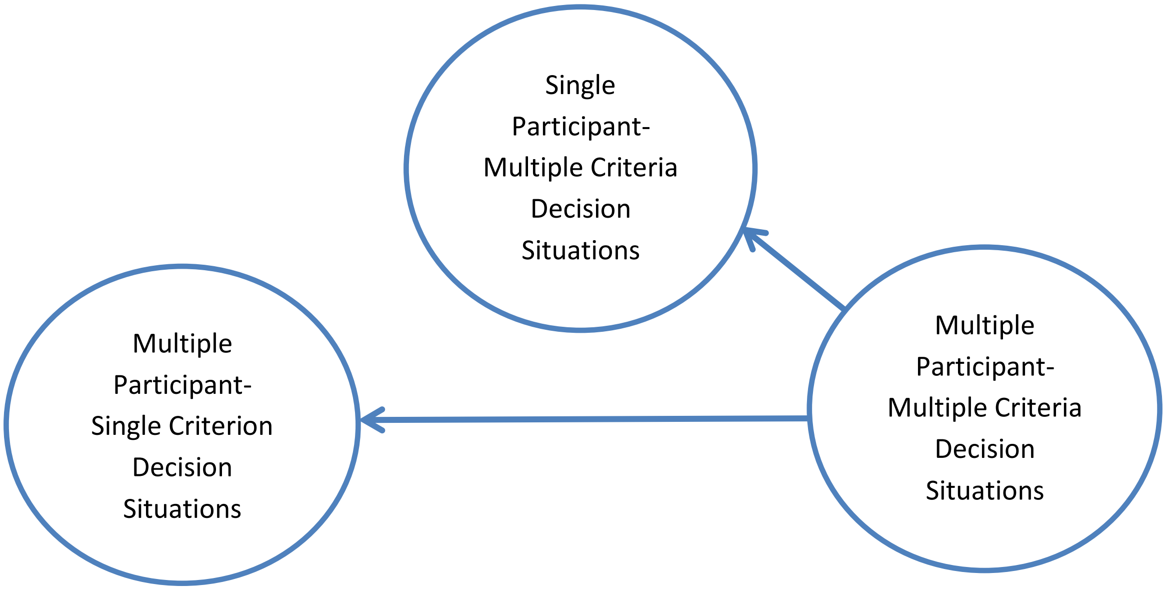

Figure 1.1.1: Relationships of decision making scenarios (Hipel et al., 1993)

There are some situations where an MPMC decision problem can be simplified into a SPMC structure (Hipel et al., 1993). One study examined in this thesis is the selection of an emissions reduction strategy by the aviation industry. The aviation industry is a large collection of aircraft manufacturers, airlines, airport facilities, maintenance facilities, etc. but can be considered to be one decision maker in this decision context because they all have the same set of criteria. Also, several industry leaders released public statements that confirmed that their preferences were very similar. This study features two methods of analysis for this SPMC problem.

The second study examined in this thesis is focused on the fluctuation of the water levels in the Laurentian Great Lakes. There are three main decision makers: the local populace around the lakes, the shipping industry that uses the lakes to transport cargo, and the International Joint Commission (IJC), an international regulatory body charged with the care and protection of the boundary waters, including the Great Lakes, between Canada and the United States. The local DMs are determined to protest if they feel like their solution was not properly considered, the shipping DMs can choose alternate but more expensive shipping methods if they notice the selected solution affecting the flow of business, and the IJC has the power to recommend a solution to the respective governments after completing its review of all evidence. Thus each decision maker has several objectives for this decision problem, making it an MPMC decision problem. However, each decision maker has to form its preferences over the possible states of this decision problem before interacting with the other decision makers. This research is concerned with the practical application of three formal decision making techniques, which are described in Chapter 2, to two different environmental decision problems. Each technique is described in detail with examples to help illustrate the concept and its application.

1.2 Objective of Research

The objective of this research is to investigate two environmental decision making problems in order to clarify and understand what have led to the decision making behavior on the part of the participants so that insights on creating movement towards desired outcomes can be revealed. Many decision making problems are undertaken without a clear understanding of the problem's parameters and the goals and perspectives of the participants, and sometimes the solution results in situations where decision makers feel that the solution could be improved. This research focuses on applying appropriate decision making methods so that decision makers can realise the solution that their preferences would produce, and determine the changes needed to move to a more agreeable solution. In this thesis, two studies are conducted and each produces a solution by using an appropriate decision making method, which is examined to determine if it is the most desirable outcome.

The objective of the first study, Evaluating Actions towards Sustainable Aviation, is to find the combination of solutions that will best serve the aviation industry by reducing emissions and adding value to its business model. The aviation industry is a highly competitive business that has many different contributors, from airlines to aircraft manufacturers to airport personnel. Trying to identify and compare areas for sustainability improvement in such a vast network is a large task, but a good solution can have significant implications for global warming as the aviation industry produces 2 to 5% of the world's greenhouse gases (Lee, 2000). Innovations implemented by this industry may also break into other markets. If the industry decided to invest in biofuels, for example, its demand would create a large market for production and distribution which could be more easily accessed by the automobile or power industries once the market was established. When an industry looks to invest in a new technology or policy implementation, its successful use in another industry makes it a safer investment. This effect makes it easier for more industries to participate in the technology or policy, which reduces greenhouse gas emissions across several industries.

The objective of the second study, Controversy over the International Upper Great Lakes Study Recommendations, is to determine a solution given the different sets of criteria for each decision maker, which should be a compromise that all decision makers find acceptable. However, the contrasting opinions of the decision makers make a compromise that all participants accept seem unlikely. This is the case for many international issues with several interested parties and can often end in protests or international disagreements. The situations can be analyzed to determine what options and preferences as given by the decision makers led to the decision solution, but the real value would be in finding which option or preference would need to be adjusted in order to produce a more agreeable outcome for the participants. This method could be used as a conflict resolution strategy that could identify and move decision makers towards compromise.

1.3 Organization of Thesis

This thesis is divided into five chapters. The second chapter is a general overview of the concepts and methodologies used in the studies and describes the situations where decision making methods can be used throughout this thesis. The chapter also includes a brief introduction to the three formal decision making methods that are used in this thesis, with examples included. Chapter 3 describes the first study, where the aviation industry is deciding on alternatives that will reduce emissions and make their business more sustainable. This analysis features the use of the Analytic Hierarchy Process (AHP) to obtain the weights for criteria as well as alternative interdependence, which compares each alternative to each other alternative to determine if there is any increased benefit to selecting two alternatives instead of one alternative. The decision makers in this study have a collaborative relationship to achieve common objectives across the industry. The second study is presented in Chapter 4, and describes an international effort to resolve the fluctuating water levels in the Laurentian Great Lakes. The decision makers belong to the local communities, the shipping industries, and the International Joint Commission, which is tasked with regulating the use and protection of the Great Lakes. The decision makers are in conflict in this situation because of their competing interests and priorities. The thesis is concluded with Chapter 5 dedicated to a summary of the work produced and proposals of future work. Lastly, interdependence tables used to resolve the analysis for the first study is documented in the appendix, which is followed by the references used in this work.

Chapter 2. Multiple Participant–Multiple Criteria Decision Making Methods

2.1 Introduction

When facing a multiple participant-multiple criteria decision problem, where can one start with untangling the problem where everyone has a different opinion of what the solution should be? If an analysis method is being selected, it is best to choose a method that fits the nature of the problem. For example, there are different methods that can be used if the decision participants are collaborative or in conflict. If the problem is attempted to be solved based on the selection of a particular solution, bias is introduced into the analysis that influences the decision, which renders the analysis useless. Considering these statements, a conclusion can be drawn that the most critical part of solving a problem is, in fact, its definition. If a problem is poorly defined, misunderstood and misleading information is given to the participants, which can filter through the analysis and produce inaccurate results. However, if a problem is clearly defined, the participants can choose their positions and alternatives based on their stake in the problem, which is evaluated by their objectives.

In order to define their objectives, the first question that one should ask is why the decision makers are interested in the problem in the first place (Keeney, 1992; Keeney et al., 2007). If their interest can be broken down into its fundamental components, a much clearer understanding of the decision maker's values, expectations and requirements can be seen. Conventional approaches to decision making rely on identifying different alternatives for solutions, meaning that a decision maker will jump from being presented with a problem to immediately considering possible solutions (Keeney, 1996). Only after the alternatives are identified will the decision maker consider objectives or criteria to evaluate the alternatives. However, alternatives are relevant only because they are a means to express and achieve values (Keeney, 1996). A value must be defined explicitly so that objectives, which provide the criteria that are used to evaluate solutions, may be defined clearly. A value is generally a simple statement that shows a principle or commitment that the decision maker has made. For example, a business person will value profits because it is the only way to keep the company solvent.

To be well defined, an objective must have a decision context, an object, and a direction of preference (Keeney, 1996). For example, if a government wishes to install a dam, one objective may be to "minimize environmental impacts". In this objective, the decision context is the harnessing of potential energy, the object is environmental impact, and the direction of preference is to lessen any impact as opposed to creating more impact (Keeney, 1996).

Now that the problem is defined and the stakeholders have defined values and objectives, a solution method for the problem can be selected. Three methods are explored below, each with a particular application and its own restrictions.

2.2 Multiple Criteria Decision Making

2.2.1 The Additive Value Function

Many multiple criteria decision making methods require the decision maker to weigh criteria and to determine the desirability (value) of an alternative in terms of each criterion. Then an additive value function for each alternative is created, which is a weighted sum of the values in terms of the criteria, as follows (Rajabi et al., 1998; Hobbs and Meier, 2000).

$$v(a) = \sum_{p=1}^{n} w_p c_p(a) \tag{2.1}$$

The above formula shows $v(a)$ as the value of *alternative a*, w_p as the weight of *criterion p*, $c_p(a)$ is the evaluation of alternative *a* on criterion *p*, and n as the number of criteria. To find the alternative value, it is necessary to determine the weights (w_p) for the criteria and the desirability, or value, of the alternative for each criterion $c_p(a)$. In other words, the alternative value is the sum of the criterion weight multiplied by the desirability of the alternative for the criterion.

This method is widely used because of its simplicity and the robustness of its results (Hobbs and Meier, 2000). One analysis method where the additive value function is used is the Analytic Hierarchy Process (Saaty, 1977, 1980), which is often used to analyze single participant-multiple criteria (SPMC) problems. Remember that SPMC problems have discrete alternatives that are evaluated against different criteria in order to rank the alternatives.

2.2.2 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a systems analysis method that is used in situations where factors in the decision process can be arranged in a hierarchy. For this method, a decision maker ranks factors important to that decision in a hierarchic structure that begins with the goal and descends to criteria, sub-criteria and alternatives (Saaty, 1980). There are two reasons for arranging the goal, criteria, and issues in a hierarchy: it provides an overview of the relationships in the situation, and helps the decision maker decide whether the issues in each level are of the same order of magnitude (Saaty, 1990). If two factors are going to be compared, they must be of a similar magnitude to provide a meaningful answer to the stakeholder. Once the factors are of comparable importance, they can be individually evaluated using a suggested scale that provides a way for the stakeholder to empirically express his/her opinion, which is given in Table 2.2.1 (Hobbs and Meier, 2000). The scale shows only odd numbers. Even numbers and decimals can also be used to express an opinion that is in between two of the odd numbers on the suggested scale. When the evaluations are complete, the comparisons are judged in a pairwise fashion by using matrices. In each matrix, subcriteria on the left are compared with those on top as to their importance with respect to the criteria being evaluated (Saaty, 2008). Next, criteria on the left are compared with those on top as to their importance with respect to the goal. Then, the subcriteria values are weighed by the weight of their parent criterion to obtain their overall value (Saaty, 2008).

Table 2.2.1: Suggested Scale for AHP Ratio Assessments (Hobbs and Meier, 2000; Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal importance	If two criteria are judged to be equally important
3	Moderate importance	If Criterion A is judged to be moderately more important than Criterion B
5	Strong Importance	If Criterion A is judged to be strongly more important than Criterion B
7	Very strong or demonstrated importance	If Criterion A is judged to be very strongly more important than Criterion B
9	Extreme importance	If Criterion A is judged to be extremely more important than Criterion B

It can be helpful to use an example to demonstrate a method. Consider the opinion of two people about a selection of fruit. The first person, Dave, has a preference for apples while Jack prefers oranges and pineapples. The goal of their discussion is to prove which fruit is the best. They have decided to evaluate the fruit in terms of tastiness and how easy it is to eat. The hierarchy for this problem is shown in Figure 2.2.1.

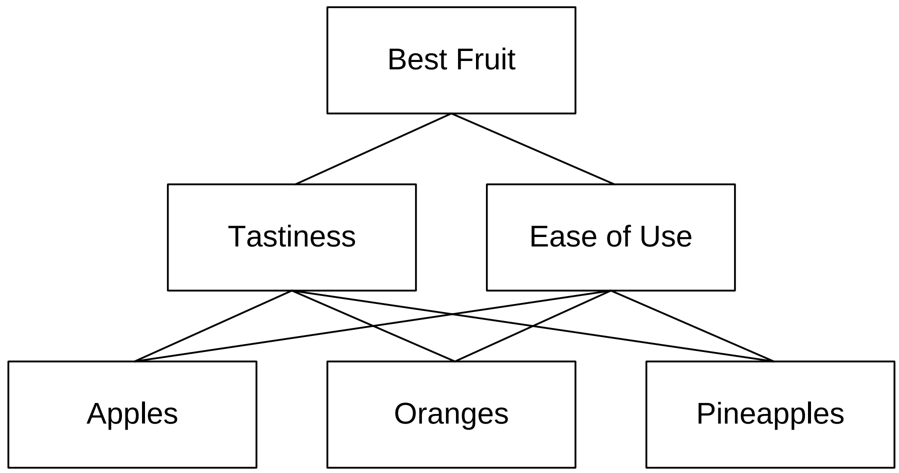

Figure 2.2.1: Hierarchy of fruit example

Now that the hierarchy is established, the comparisons of alternatives with respect to each criterion can be expressed in tabular form as shown in Tables 2.2.2 and 2.2.3 by using the suggested scale for AHP ratio assessments. In these tables both stakeholders agree through discussion that pineapples taste the best but are the hardest to eat, oranges are in the middle when it comes to taste and ease, and apples are the least tasty and the easiest to eat.

Table 2.2.2: Alternatives compared with respect to tastiness

Alternative		**Alternative**		**Reasoning**
Apples	1	Oranges	2	Oranges taste slightly better than apples
Oranges	1	Pineapples	2	Pineapples taste slightly better than oranges
Pineapples	4	Apples	1	Pineapples are significantly tastier than apples

Table 2.2.3: Alternatives compared with respect to ease of use

Alternative		**Alternative**		**Reasoning**
Apples	3	Oranges	1	Apples are moderately easier to eat than oranges
Oranges	2	Pineapples	1	Oranges are slightly easier to eat than pineapples
Pineapples	1	Apples	5	Apples are much easier to eat than pineapples

Now information contained in Tables 2.2.2 and 2.2.3 is expressed in matrix form, as shown in Tables 2.2.4 and 2.2.5 for the criteria of tastiness and ease of use, respectively. Each matrix must have a diagonal of one and each value entered must be reciprocated. Once the matrix is assembled, the value of each alternative in terms of the specific criterion is found using the principal right eigenvector of the matrix, which can be calculated by hand or by a program.

Table 2.2.4: Value of alternatives on the criterion of tastiness

Taste	Apples	Oranges	Pineapples	Value
Apples	1	1/2	1/4	0.1429
Oranges	2	1	1/2	0.2857
Pineapples	4	2	1	0.5714

Table 2.2.5: Value of alternatives on the criterion of ease of use

Ease of use	Apples	Oranges	Pineapples	Value
Apples	1	3	5	0.6483
Oranges	1/3	1	2	0.2296
Pineapples	1/5	1/2	1	0.1221

Now that the values of the alternatives with respect to both criteria are found, there must be a comparison of the criteria to determine the weight of each criterion, as given in Tables 2.2.6 and 2.2.7.

Table 2.2.6: Criteria compared

Criterion		**Criterion**		**Reasoning**
Tastiness	2	Ease of use	1	Tastiness is slightly more important than ease of use

Table 2.2.7: AHP matrix with respect to criteria

Criteria	Tastiness	Ease of use	Weight
Tastiness	1	2	0.6667
Ease of use	1/2	1	0.3333

Once the weights of the criteria are determined, the overall value for each alternative can be calculated by using Equation (2.1). The results are shown in Table 2.2.8.

Table 2.2.8: Solution for fruit example

Alternative	Weight for Tastiness	Value for Tastiness	Weight for Ease of Use	Value for Ease of Use	Overall Value
Apples	0.6667	0.1429	0.3333	0.6483	0.3114
Oranges	0.6667	0.2857	0.3333	0.2296	0.2671
Pineapples	0.6667	0.5714	0.3333	0.1221	0.4216

According to Table 2.2.8, pineapples are preferred over apples, and apples are slightly preferred over oranges. If Jack or Dave has doubts about the results of this analysis, the clarity of the steps allow them to make changes to their preferences or weights in the necessary places. However, there can be uncertainly in the pairwise comparison as they are based on decision makers' opinions. If a decision maker cannot express an opinion with certainty, for example being unable to decide between two values, it introduces uncertainty into the system. The uncertainty corresponding to this opinion can be expressed as a fuzzy value. To determine the effect of the fuzzy variable, a sensitivity analysis or a fuzzy analytic hierarchy process can be performed (Van Laarhoven and Pedrycz, 1983).

2.2.3 Interdependence of Alternatives in Multiple Criteria Decision Making

In many multiple criteria decision making problems, selecting more than one alternative to solve a problem is often a better solution than selection only one alternative. These alternatives can be conditionally or unconditionally interdependent. Two alternatives are unconditionally interdependent when two alternatives affect each other via a criterion no matter what other alternatives are chosen, and are considered conditional when the effect they have on one another only holds when some or only one alternative is chosen (Rajabi et al., 1999). For example, using biofuels instead of petroleum for aviation is unconditionally interdependent with the economic alternatives because biofuels are currently two or three times more expensive than petroleum, which leads to comparatively higher recurring fuel costs. Criteria for evaluating these alternatives must also be considered. Once the criteria are determined, the decision makers are asked to define their preferences for each criterion, which is called a weight, as discussed in Section 2.2.1. Each alternative is then judged based on each criterion and the result is expressed in a value, where a higher value indicates a favorable result. As given in Equation (2.1), the sum of the value of the alternative for the criterion multiplied by the criterion weight gives the alternative value. At this point, interdependence has not been factored into the analysis.

To include interdependence between alternatives, the interdependence must first be defined based on the synergy of the alternatives suspected to be interdependent (Rajabi et al., 1998). For the sustainable study in Chapter 3, if there is a twenty percent increase in industry value if both the algae and high bypass engine solutions are selected, it can be said that there is a positive synergy of twenty percent. However, if another combination of alternatives reduces the value of the solution, it can be said that it has a negative synergy (Rajabi et al., 1998). Once the synergy of each combination of two alternatives is determined per criterion, the alternative values, as found in Equation (2.1), of both alternatives in the combinations are added and multiplied by the synergy percentage (Rajabi et al., 1998). This is repeated for all non-repetitive combinations of alternatives and the combination with the highest score is selected as the best solution (Rajabi et al., 1998).

2.3 The Graph Model for Conflict Resolution

The Graph Model for Conflict Resolution (GMCR) was developed as a method for studying strategic conflicts involving multiple participants, each of which has multiple criteria, in a flexible and approachable way. GMCR uses states as the basic units for describing a conflict (Fang et al., 1993; Hipel et al., 1997). This methodology represents a conflict in a graphical way as the movement from one state to another (the vertices of a graph) via transitions (the arcs of the graph) which are dictated by the decision makers (Fang et al., 1993; Hipel et al., 1997). A particular advantage of this method is that it can incorporate irreversible moves, where a decision maker may move unilaterally from one state to another, but cannot make the reverse move. The graph model can also show common moves in which one or more decision makers can move from one state to another (Fang et al., 1993; Hipel et al., 1997).

The general method of applying GMCR is shown in Figure 2.3.1, consisting of two main phases of modeling and analysis. The first three steps are concerned with problem definition, and arguably the most important part of the analysis. If a problem is not defined correctly, the analysis will not produce an accurate result. The next two steps define the states of the conflict and the moves that are allowable between states. These steps define the movement between states and the limitations of that movement as a way of describing the conflict. The last step in the modeling phase is the definition of relative preferences of the decision makers, reflecting their values and objectives. The analysis of the conflict can now begin, which starts with using stability solution concepts to find the individual stability of each state and through them, the equilibria of the conflict. Once the equilibrium solutions are found, it can then be tested for their sensitivity to change, which describes the robustness of the results. This information is then relayed to the decision makers to aid in their decision making process.

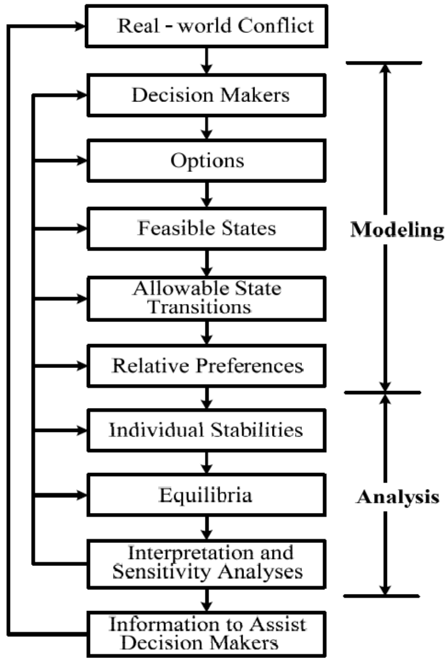

Figure 2.3.1: Applying the graph model for conflict resolution (Hipel et al., 2012)

This process is best visualised through an example. The Prisoner's Dilemma is a simple example of a conflict to be resolved using the GMCR method and includes two options for two decision makers (Bristow, 2014). The Prisoner's Dilemma is a well-known game in the literature (Rapoport and Chammah, 1965). Two burglars were apprehended by the police and are being held in two separate interrogation rooms without a way to communicate with each other. The police offer each prisoner the same deal, to confess and give evidence against the other prisoner and the punishment will be light, or be convicted under the other prisoner's testimony and receive a harsher sentence than if he voluntarily confessed. For the option of betraying his partner and being released, the payoff is designated as +2. If the prisoner stays silent and is convicted by the other's testimony, the payoff is -2. If both prisoners remain silent the payoff is +1 and if both confess the payoff is -1. The game is represented in tabular form in Table 2.3.1 (Rapoport and Chammah, 1965).

Table 2.3.1: The Prisoner's Dilemma (Rapoport and Chammah, 1965)

Prisoners' Dilemma		**Prisoner B**	
		Do not confess	Confess
Prisoner A	Do not confess	(1, 1) (state 1)	(-2, 2) (state 3)
	Confess	(2, -2) (state 2)	(-1, -1) (state 4)

Now that the decision makers, options and feasible states are defined, the modeling can move onto the description of state transitions. As shown in Figure 2.3.2, the solid line represents the transitions available to Prisoner A, and the broken line represents the transitions available to Prisoner B.

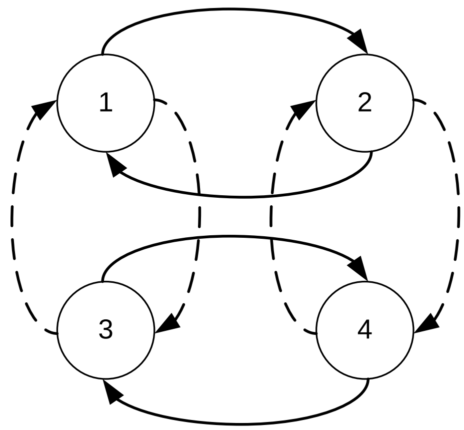

Figure 2.3.2: Graph model of Prisoner's Dilemma

Now that the state transitions are defined, decision makers' preferences are next on the process of applying the method. Prisoner A would prefer if it confessed and Prisoner B did not, and Prisoner B most prefers it if it confessed and Prisoner A did not based on the payoffs given in Table 2.3.1. The next preference for both prisoners is for neither of them to confess, and the least preferred state for both is when it does not confess but the other prisoner does. This is represented in Table 2.3.2.

Table 2.3.2: Decision makers' preferences for the Prisoner's Dilemma

Decision Makers (DMs)	**Most Preferred**			**Least Preferred**
Prisoner A	2	1	4	3
Prisoner B	3	1	4	2

These transitions can be considered irreversible because a confession is difficult to retract, and there is only a limited time available to confess so a prisoner cannot confess after that time. The irreversibility is represented by arrows that point in the only direction that a decision maker can move, as shown in Figure 2.3.3.

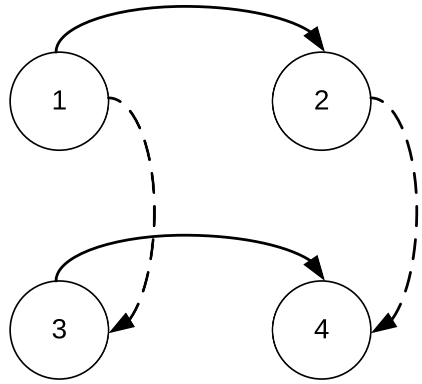

Figure 2.3.3: Irreversible moves for Prisoner's Dilemma

Once a graph model for a conflict is completely defined, each state is examined for stability, where stability is defined as a state that a decision maker prefers not to move away, and instability is when a decision maker prefers to move from a state, based on a defined solution concept (Fang et al., 1993). To reflect decision makers' behavior under conflict, a variety of solution concepts, including Nash stability (R), general metarationality (GMR), symmetric metarationality (SMR), sequential stability (SEQ), limited-move stabilities (L_h), and non-myopic stability, have been defined within the graph model for conflict resolution (Fang et al., 1993). When a state is stable for all decision makers under a solution concept, it is an equilibrium under the particular solution concept (Fang et al., 1993). An equilibrium is considered as a possible resolution of a conflict.

For Prisoner's Dilemma with irreversible moves given in Figure 2.3.3 and Table 2.3.2, States 2 and 4 are stable for Prisoner A and States 3 and 4 are stable for Prisoner B under Nash stability. Thus State 4 is an equilibrium for this conflict under Nash stability. A sensitivity analysis could be carried out on this conflict to determine its robustness, but the concept is covered in detail in Chapter 4.

Chapter 3. Evaluating Actions towards Sustainable Aviation

3.1 Introduction

A classic definition of sustainability is to satisfy the needs of the present without compromising the ability to satisfy the needs of the future (UNWCED, 1987). However, there are major issues that the aviation industry is currently facing that could prevent the industry from being able to accommodate the needs of future travellers without causing environmental damage that will make the industry unsustainable. The most obvious issue is that the use of aircraft in a rapidly expanding market produces carbon dioxide and other greenhouse gases, which contribute to climate change (Lee, 2000; Taylor, 2015). Aircraft manufacturing also causes greenhouse gas emissions from the manufacturing process as well as the shipping of parts from one country to another to make the manufacturing process more affordable. The presence of greenhouse gases in the atmosphere greatly contribute to a phenomenon known as radiative forcing, which is the driving force behind climate change (Lee, 2000; Taylor, 2015). Some of the research in this chapter is appeared in a conference paper by Karnis et al. (2015b).

3.2 Sustainability in the Aviation Industry

3.2.1 Environmental Background

Radiative forcing, or the amount of light from the Sun absorbed by the atmosphere, has been an area of significant political and scientific study in the last 25 years. The Sun's rays that strike the Earth are either reflected back into space by the atmosphere, absorbed by the atmosphere or absorbed by the Earth. The amount of energy absorbed by the atmosphere is known as radiative forcing, and can be described as positive or negative forcing depending on if the atmosphere is being heated or cooled (Dray et al., 2010; Evans, 2013). A large scientific body of evidence shows that the human contribution to forcing is creating long term changes in the Earth's climate. Studies of atmospheric carbon dioxide (CO_2) emissions, one of the key causes of forcing, rank China, the United States and the European Union as the top emissions generators respectively (PBL Netherlands Environmental Assessment Agency, 2015). This is relatively predictable as these countries also have the highest populations and largest economies (Taylor, 2015). Less obvious is that specific economic sectors such as commercial aviation contribute significantly on a global scale to radiative forcing. Studies have shown that commercial aviation is responsible for between 2 and 5% of global CO_2 emissions (Lee, 2000; IMF and World Bank, 2011). If the industry were a country, it would rank as between the 5th and 7th highest CO_2 emission state in the world (Taylor, 2015). This is further compounded by the fact that the commercial aviation industry is growing at a high rate of (on average) 5% per year, mostly in emerging markets (Taylor, 2015).

As commercial aviation is responsible for a significant portion of global radiative forcing, it has come under significant pressure to produce methods to reduce the sector's contribution to global forcing. George Monbiot, author of Heat of the Moment, says that "aviation has been growing faster than any other sources of greenhouse gases … and unless something is done to stop this growth, aviation will overwhelm all the cuts we manage to make elsewhere" (Monbiot, 2006). The International Commercial Aviation Organization (ICAO) committed to several goals given to it by the Kyoto Protocol in 1998, which were to reduce emissions per passenger/km and cargo/km by 2% by 2020, carbon neutral growth past 2020, and a 50% reduction in greenhouse gas emissions from current levels by 2050 (ICAO, 2014). However, the ICAO goals are not enforceable by the Kyoto accords. These goals become more daunting when the present high rate of industry growth is considered. To achieve this reduction the aviation industry plans to implement a wide variety of counteracting measures, like biofuels, advanced design, alternate methods of travel and market based incentives.

3.2.2 Possible Technologies

Future use of biofuels by the aviation industry is projected to represent as much as 50% of projected net reduction in greenhouse gases (Dray et al. 2010). Biofuels reduce greenhouse gas (GHG) emissions by recapturing CO_2 already present in the atmosphere and reusing it as a fuel (Dray et al. 2010; Evans, 2013). In theory the practice is 100% carbon emission neutral as it does not add any new CO_2 to the atmosphere. In reality, the significant industrial processes reduce this efficiency significantly, but nevertheless current biofuels can already be 60-70% emission neutral. There is also research showing that biofuels can be tailored to reduce nitrogen oxide emissions, another short-lived but powerful GHG (Dray et al., 2010; Evans, 2013). Current barriers to adoption stem from the high cost of refining bio-matter into the fuels (Lee, 2010) and from the controversy of using some human consumed crops such as corn for fuel production (Taylor, 2015). However, companies in the industry have already declared their interest in biofuels despite the costs (Air Canada, 2014; Boeing, 2015).

Development of advanced aircraft also represents a significant portion of projected future CO_2 emissions reduction. This will include the natural progression of some trends already seen in the industry such as the increased use of highly advanced composite materials to reduce aircraft weight and the use of geared high-bypass turbofans to improve engine efficiency. Future development may include implementation of more unconventional but highly advanced fuselage designs including blended wing bodies and closed wing designs (Evans, 2013). These designs should also be able to support highly advanced extreme high bypass or open rotor turbofans. Another area of significant study will be advanced regional jet design with extreme high aspect ratio wings and ducted engines (Evans, 2013). One area of significant difficulty is that the most frequently used commercial aircraft (i.e. Boeing 737 and Airbus A320) are quite small aircraft. Their low cost, highly competitive market and even their physical dimensions have limited the influx of advanced technologies often seen in the manufacturers' larger models (Dray et al., 2010; Evans, 2013). However it is important to note that barring dramatic new discoveries the contribution to net emissions from these changes will be small. It can be seen from trend data of aircraft in the last 50 years that aircraft efficiency improves at a rate of approximately 1% per year (Dray et al., 2010; Evans, 2013). Furthermore, this improvement has largely plateaued as the development of high bypass engines which improved engine efficiency dramatically has been limited by maximum turbine blade temperatures. Similarly incremental performance gains in fuselage design have also been limited in overall efficiency improvement (Dray et al., 2010; Evans, 2013).

There is also the option of modifying flight parameters and general standards of practice. Modifying flight parameters have been studied extensively. Modern commercial aircraft fly at high altitudes and speeds. Studies have shown that reductions in cruise speed and altitude can lead to significant reductions in net radiative forcing from current fleets of commercial aircraft by reducing the reflective area of their contrails, or condensation trails (Lee, 2000; Evans, 2013). These reductions can be further improved by custom designing future aircraft to fly in these envelopes. More effective operations of aircraft may also yield some reductions including flying aircraft in formation to provide slip streaming to other nearby aircraft, the use of constant descent air traffic control protocols (Boeing, 2015) and the use electrical on ground tow taxiing to reduce emissions production on the ground (Lee, 2000; Evans, 2013). The reduction in emissions is proportional to the reduction in fossil fuels used, which can be expressed as the average reduction of block fuel burn per aircraft. Table 3.2.1 gives reduction in average block fuel usage per aircraft for possible alternatives to reduce GHG emissions (Evans, 2013). The term block fuel includes the fuel used during all parts of an aircraft's use, including start, taxi out, take-off, climb, cruise, descent, approach, landing, and taxi into the terminal.

Table 3.2.1: Reduction in average block fuel usage per aircraft for possible alternatives to reduce GHG emissions (Evans, 2013)

Alternative Group	**Alternative**	**Average Block Fuel Usage Reduction % per Aircraft**
Advanced aircraft design	High bypass turbofans or open rotor turbofans	46
	Blended wing and closed wing designs with ducted engines	30
Standards of Practice and Flight Parameters	Reduce altitude and cruise speed	4.6
	Constant descent air traffic control	1.6
	Electrical tow cars and other ground vehicles	3
Economics	Retire aging aircraft older than 25 years	10.4

3.2.3 Sustainability and Economics

The aviation industry, not including its satellite industries like materials manufacturing, contributes $2.4 trillion USD to the world's economy, or 3.4% of the global GDP (Evans, 2013). Global aviation has a current and forecasted revenue passenger-kilometers growth of approximately 5% a year for the foreseeable future (Evans, 2013). This means that the amount passengers travelling are increasing by about 5% a year every year fairly consistently, mostly due to emerging markets in East Asia and India (Evans, 2013). The large demand created by these new markets has made the need for increased aircraft efficiency more obvious. However, there has only been about a 1% increase in aircraft efficiency a year related to technological improvements at great expense (Evans, 2013). Figure 3.2.1 shows the reduction in energy consumed by aircraft in the past and predicted reduction in the future if the aging aircraft are retired early to reduce emissions by purchasing a newer, more efficient plane as well as if all technological measures are implemented.

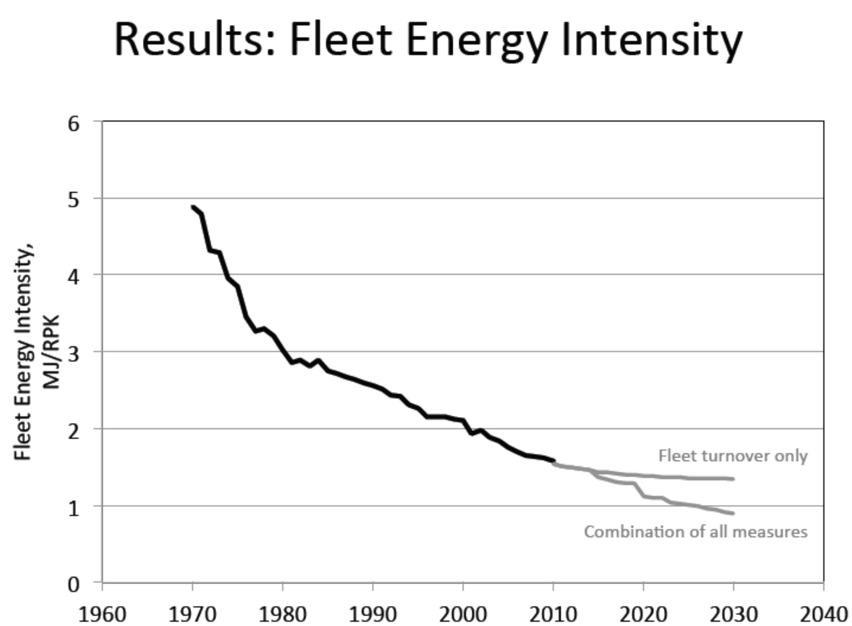

Figure 3.2.1: A graph of the reduction in fleet energy intensity over a span of eighty years (Evans, 2013)

Since the reduction in energy used is becoming stagnant even with the introduction of new technologies and early aircraft retirement, a market based approach may be the next step to allow the aviation industry the potential for profit through carbon trading. It can be seen that aircraft are particularly difficult to optimize highly for low net radiative forcing due to the physical constraints of flight and the low yield of current research limit improvements in aircraft performance. Treaties such as the Kyoto Accord utilize market based instruments such as carbon trading to help entities reduce net global emissions with the greatest monetary efficiency by permitting the purchase and sale of carbon credits (IMF and World Bank, 2011;Taylor, 2015). This allows a third party entity such as a developing country where required improvements may be more economically feasible and less technologically complex to support this net emission reduction. Market based instruments such as the carbon tax also incentivizes companies to reduce their emissions and thus their costs while placing them on competitive footing with other companies. It could even encourage development of alternative forms of travel especially to replace short-haul flights with other technology like high-speed trains. The current economic climate of advanced aircraft research requires significant financial expense to engine and aircraft manufacturers which achieves only minimal gains (Taylor, 2015). This creates an environment of “wait and see” where manufacturers wait for one another to make the first move and observe if it is a successful expenditure. Market based instruments can also stimulate fleet turnover. The average lifespan of commercial aircraft span 30 years or longer and there is a significant delay between when new technology is commercially available and before it becomes attractive to aircraft owners to purchase new aircraft. Due to this it may be as long as 15 years on average before fleet turnover reaches >50% of all fleet aircraft. An incentive program similar to “cash for clunker” programs for cars can encourage airlines to replace aircraft sooner and thus promote the arrival of new technological benefits sooner (Taylor, 2015).

3.2.4 Sustainability and Society

Alternatives to air travel can also be seriously considered. Significant portions of overall commercial air traffic are short non-international flights, sometimes referred to as commuter flights. These flights can be replaced using modern high speed rail links. Due to long overhead time to clear security and retrieve baggage actual flight time of short-haul flights represents only a fraction of overall travel time. Also, the short travel distance results in aircraft flying at lower speeds and altitudes, so regional aircraft with lower cruising speeds are used. These flights could potentially be replaced with modern Maglev or high speed electrical trains (Evans, 2013). The usage of trains permits simplified access to renewable and high efficiency electrical energy infrastructure which is difficult to access with aircraft. Trains are not as restricted as aircraft when it comes to weight restrictions, which means that there is more allowances for head, leg, and seat room, which can create a more pleasant experience. There are some concerns that the public will not adjust well to using trains instead of airplanes for transit, but they are mitigated when one acknowledges the situation in China. China has recently added thousands of kilometers to its high speed rail lines, bringing the total distance covered by high speed rail to over 12,000 kilometers

(WBG, 2014). The trains have been hugely popular, with an increase in trips from 128 million in 2008 to 672 million trips in 2013 (WBG, 2014). Overall, 2.9 billion people have taken the train from April 2007 to October 2013 (WBG, 2014). Studies of the demographic using the high speed train indicated that the passengers were largely between the ages of 22 and 55, and were using the train for business trips (WBG, 2014). Since the high speed train was so well received in China, there is significant reason to believe that it will be well received by other populous countries. High speed trains also have the added benefit of producing only 30-70 grams of CO_2, per passenger-kilometer, versus the 150 grams produced by cars and the 170 grams produced by airplanes (WI, 2013).

Reduction in the global radiative forcing contribution of the commercial aviation industry is a substantial task that has significant barriers due to current technological and economic limitations. The aviation industry has already improved their net emissions by addressing the “low hanging fruit” of easily upgraded fleets and the replacement of older technologies, which means that future improvements will be more difficult (Dray et al., 2010). Many industry leaders have developed a roadmap of how they plan to address this issue and it includes a wide variety of current and future technological developments as outlined above. If these goals are not met, the failure will likely contribute to the rising of the global average temperature (Lee, 2010). However, the aviation industry needs to work integratively in this regard as the results of carbon reductions is unlikely to be achieved by a sole party. For example, carbon markets and economic incentives may be implemented by ICAO in cooperation with governments and these may enable or promote manufacturers and airlines to adopt alternative fuels and flight planning strategies.

3.3 Interdependence of Alternatives

3.3.1 Criteria and Preferences

When a large investment is considered, there are many factors that need to be reviewed. The criteria are first defined then are expanded to include the preference of the aviation industry. Table 3.3.1 summarizes the criteria to be considered in this analysis. For a project to be contemplated, it must at least have a neutral (or break-even) return on investment (ROI) that can be measured in terms of profit, added value or cost savings. There are other factors that must be recognized that cannot be measured purely in terms of capital. Carbon dioxide is the GHG with the longest half-life (Lee, 2000), and thus must be reduced as much as possible to meet ICAO goals. It may also be beneficial to produce less carbon dioxide to reduce possible carbon taxes. An airline or an aircraft manufacturer schedules flights and builds aircraft on a schedule that must be strict to ensure profitability. If changes are implemented that disturb this schedule, it will create delays and lost profit along the supply chain and also irritate passengers waiting for their flight. Therefore, a new project should ideally be minimally intrusive so that the normal flow of business is disturbed as little as possible. The last factor is the opinion of a company's stakeholders and customers. If a project adds meaningful value to the company, through higher customer opinion of the experience, it can be considered popular.

Table 3.3.1: Criteria and general preferences of the aviation industry

Criteria	Explanation
Return on Investment (ROI)	The ROI is estimated from the comparison of the profit earned from the initial investment to the initial investment (Fraser and Jewkes, 2013). The aviation industry would prefer to have a profitable return on investment, or at least break even.
CO_2 Emissions (CO_2)	Since CO_2 is the main GHG to be reduced, a solution is preferred if it produces less CO_2 than its competitors.
Minimal Disruptions (Min. Dis.)	A quick implementation of the resolution would provide the least disruption in the regular flow of business, which would save the industry money.
Popularity (Pop.)	A program is defined as popular if it attracts more customers than it dissuades. A popular program would increase or at least stabilize sales, which also contributes to a favorable ROI.

While these criteria are all valued, they are not considered of equal importance (Saaty, 1980). In Chapter 2, the analysis was described as needing the criteria to be weighted as a way to express the decision maker's priorities. Also, Section 3.2.1 mentioned the voluntary goals outlined by the ICAO that the aviation industry committed to in the Kyoto accords. In this case, profit should be ranked higher than meeting ICAO goals because the decision to save money by creating efficiencies will inadvertently progress towards the ICAO goals, though the industry may not make the emissions cuts they promised by 2050. The industry must also remain profitable to remain in business and satisfy its shareholders, so the ROI criterion should the most heavily weighted. Each of these criteria can cause significant and costly problems if it is not weighted appropriately and is neglected. The weights can be found using an AHP analysis as described in Section 2.2.2. Below is a diagram of the hierarchy.

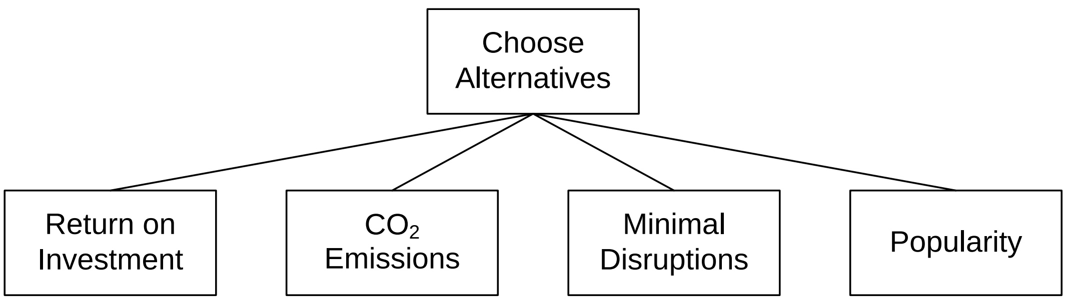

Figure 3.3.1: AHP hierarchy for weights

The suggested scale for pairwise comparisons in Table 2.2.1 can now be used to weight the criteria in terms of the overall goal. Tables 3.3.2 and 3.3.3 are the comparison tables, where the weight for each criterion is also calculated. Please note that the weight is another name for the principal right eigenvector of the matrix, which is found using algebraic methods.

Table 3.3.2: Comparison of alternatives

ROI	3	CO_2	1	ROI has an advantage over CO_2 emissions reduction because ROI is needed in the short term to ensure business sustainability.
CO_2	1	Min. Dis.	2	Minimal disruptions is more important than emissions reduction for business sustainability because it has a more immediate effect on customer satisfaction.
Min. Dis.	2	Pop.	1	Minimal disruptions is marginally more important than popularity because an airline with long delays will soon become unpopular.
Pop.	1	ROI	4	ROI is more important than popularity because an airline can still go bankrupt due to popular but unprofitable policies.
ROI	4	Min. Dis.	1	ROI has an advantage over minimal disruptions because ROI provides the capital to keep the business running.
CO_2	4	Pop.	1	Emissions reduction is more important than popularity because reducing emissions will increase popularity through price reductions and by being seen as more environmentally friendly.

Table 3.3.3: AHP matrix for sustainable aviation

AHP	ROI	CO_2	Min. Dis.	Pop.	Weight
ROI	1	3	4	4	0.5233
CO_2	1/3	1	1/2	4	0.1874
Min. Dis.	1/4	2	1	2	0.2052
Pop.	1/4	1/4	1/2	1	0.0851

Therefore, the industry's preferences are represented in weights as follows:

$$w_{ROI} = 0.5233, w_{CO2} = 0.1874, w_{min.disrupt} = 0.2052, w_{pop} = 0.0851$$

$$w_{ROI} > w_{min.disrupt} > w_{CO2} > w_{pop}$$

Return on investment is predictably its first priority, and minimal disruptions is second. Emissions reduction is weighted slightly less than minimal disruptions, because increased delays will cost an airline its customers who will go to an airline undisrupted by emissions reductions which will raise emissions across the industry. Popularity of the emissions reduction methods is weighted the least, but it still has a significant say in the industry's decision.

Now that the industry's preferences have been quantified in the form of weights, the next step is to consider which alternatives are available for it.

3.3.2 Available Alternatives

Out of the possible alternatives available to the aviation industry as outlined in Table 3.3.4, large companies have publicly expressed interest in only a few of these alternatives. In March 2012, Porter Airlines in partnership with Bombardier conducted the first Canadian biofuel powered test flight with a Q400 aircraft (Bombardier, 2012). Bombardier has also reduced its GHG emissions by 4% through several sustainable projects when its yearly emissions from 2009 and 2013 are compared (Bombardier, 2015). However, Bombardier has ascertained that it would only be able to reach its goal of carbon neutrality by 2020 though purchasing carbon credits, but has decided that "it was not the most strategic choice for us to make" and has instead decided to focus on reducing carbon emissions by investing in energy saving products (Bombardier, 2015). Boeing has also made its commitment to reducing carbon emissions public and has invested in a three tiered approach to reducing emissions by incorporating airframe efficiency innovations (weight-saving), technology improvements to modernize the air traffic control system, and by expanding the supply of sustainable aviation biofuel for the industry (Boeing 2015). In 2014, Air Canada published a report that detailed its strategy for reducing carbon emissions (Air Canada, 2014). It specified that weight saving was one of its top priorities because fuel is its single largest expense and if every aircraft in its fleet was a kilogram lighter, it would save 24,500 litres of fuel and 63 tonnes of GHG emissions (Air Canada, 2014). It has also reduced its emissions by retrofitting Boeing 767s with winglets, which direct airflow and result in less fuel burn, and by increasing the number of seats in the Boeing 777, making it 21% more efficient (Air Canada, 2014). Air Canada has also conducted two commercial flights in 2012 using biofuel and has declared its support for further research in the area (Air Canada, 2014). Given the aforementioned, it appears that the aviation industry has a strong preference for advanced aircraft design, standards of practice and biofuel but has an aversion to carbon trading.

Table 3.3.4: Possible alternatives for aviation industry

Alternative Group	Alternatives
Biofuels	Corn fuels, Algae.
Advanced aircraft design	High bypass turbofans, Blended or closed wing designs with ducted engines.
Standards of practice and flight parameters	Reduce altitude and cruise speed, Formation flying, Constant descent air traffic control, Electrical tow cars and other ground vehicles.
Market driven actions	Retire aging aircraft, Carbon trading, High speed trains to reduce short haul flights.

The consequences of implementing these alternatives are described in numerical form in Table 3.3.5. These numbers are described as percentages, and some in the ROI row are taken from Table 3.2.1 where the alternative is described as a reduction in block fuel burn (Evans, 2013). The higher the percentage, the higher the alternative is judged to perform on that criterion.

Table 3.3.5: Normalized consequences of eleven alternatives (in percentages)

	Biofuels		**Advanced Aircraft**		**Flight Parameters**				**Economics**			
Criteria	Corn	algae	high bypass engines	blended wing	reduce altitude	formation flying	constant descent	Elec. ground vehicles	retire aging aircraft	carbon trading	high speed trains	**Weights**
ROI	50	60	46	30	4.6	10	1.6	3	10.4	30	25	0.5233
CO_2	60	70	80	50	10	5	5	10	20	60	50	0.1874
Minimal Disruption	70	90	80	10	65	50	10	70	50	5	20	0.2052
Popularity	10	50	60	30	10	10	10	60	70	20	75	0.0851

3.3.3 Interdependence of Alternatives

Some of the alternatives listed in Table 3.3.4 can have a direct effect on other alternatives. This effect is called the interdependence of alternatives and must be included in the analysis to produce an accurate result (Santhanam and Kyparisis, 1993). If two actions are not interdependent, they are assumed to be independent (Kidd, 1990). Table 3.3.6 shows some basic interdependence between the alternative groups.

Table 3.3.6: Examples of interdependence of alternatives in sustainable aviation

Groups of Alternatives	Criterion	Type	Description
Biofuels and market driven actions	ROI	unconditional	Biofuels would reduce the number of carbon credits needed per aircraft compared to petroleum.
Advanced aircraft and standards of practice	Minimal disruptions	unconditional	New engines, wings or bodies would require different maintenance, crew training and possibly airport infrastructure, which means that new standards of practice will need to be implemented.
Biofuels and advanced aircraft	CO_2	unconditional	New engines can be designed for biofuels to further increase fuel efficiency, which can additionally reduce CO_2.
Advanced aircraft and market driven actions	ROI	unconditional	New technology makes retiring or selling older aircraft more economical as it minimizes usage costs.

There are more detailed interactions between the specific alternatives, which are measured on the scale in Table 3.3.7. A positive interdependence is when two interacting alternatives produce a positive result in terms of the criteria with which they are being evaluated. A negative interdependence describes a situation where the two alternatives produce a less favorable result (Rajabi et al., 1999).

Table 3.3.7 Interdependence rating scale

← Positive Interdependence				Negative Interdependence →
1	0.5	0	-0.5	-1

Each interdependence must be evaluated and added to the analysis to ensure a more accurate result. Interdependence ratios of alternatives with respect to each of the criteria are given in Tables A.1 to A.4 in Appendix A. Interdependence ratios for the ROI criterion are given in Table 3.3.8.

For example, the use of corn or algae biofuels with high bypass engines would produce a favorable result with respect to ROI because of the energy efficiency of the engine and the sustainable nature of biofuels. The interdependence between corn biofuels and high bypass engines is a slightly positive interdependence rating (0.2) because high bypass engines can be designed to specifically burn biofuels in the most efficient way (Evans, 2013). However, the algae biofuel has a more positive interdependence ratio of 0.4 because of the higher ethanol content that can be extracted from the bio-matter versus corn and because it needs no land to grow. There is also a slight positive interdependence between the electrical ground vehicles and carbon trading alternatives because electrical tow cars would mean that less carbon credits are used and thus less need to be bought. There is the same interdependence between high speed trains and carbon trading. There also exists a slightly positive interdependence between the alternative to retire aging aircraft and carbon trading because the replacement of older aircraft and the sale of the same aircraft will create a cascade effect where the oldest and least efficient aircraft will be replaced. An example of a negative interdependence is the relationship between formation flying and constant descent landings. If both alternatives are chosen, there will be a large number of aircraft circling the runway waiting for their chance to land, which would cause considerable delays and stress for runway personnel. If there is a small number of aircraft in formation, the stress on the airport is reduced and the solution is more feasible. Since the solution is not entirely negative, it is assigned a score of -0.5, as given in Table A.3. The numbers for all interdependences can be found in

Table 3.3.8: Interdependence ratios for ROI criterion

	corn	algae	high bypass engines	blended wing	reduce altitude	formation flying	constant descent	electrical ground vehicles	retire aging aircraft	carbon trading	high speed trains
corn	0	0	0.2	0	0	0	0	0	0	0	0
algae	0	0	0.4	0	0	0	0	0	0	0	0
high bypass engines	0.2	0.4	0	0	0	0	0	0	0	0	0
blended wing	0	0	0	0	0	0	0	0	0.1	0	0
reduce altitude	0	0	0	0	0	0	0	0	0	0	0
formation flying	0	0	0	0	0	0	0	0	0	0	0
constant descent	0	0	0	0	0	0	0	0	0	0	0
electrical ground vehicles	0	0	0	0	0	0	0	0	0	0.1	0
retire aging aircraft	0	0	0	0.1	0	0	0	0	0	0.2	0
carbon trading	0	0	0	0	0	0	0	0.1	0.2	0	0.1
high speed trains	0	0	0	0	0	0	0	0	0	0.1	0

3.3.4 Computing Impact of Interdependence

A program is designed to find the most preferred combination of alternatives. The computation is based on the method laid out by Rajabi et al. (1998). Based on the procedure discussed in Section 2.2, first the interdependence of each combination of two alternatives is determined per criterion. Then, the value of a combination for a criterion is computed in the following two steps:

1. The sum of each alternative's normalized consequence multiplied by the criterion's weight is obtained,
2. The sum obtained in the previous step is multiplied by the synergy percentage for the criterion.

The value of each combination is obtained by summarizing the value of the combination for a criterion over all of the criteria. This is repeated for all non-repetitive combinations of alternatives and the combination with the highest score is selected as the best solution (Rajabi et al., 1998).

Once the interdependence ratio tables are completed, the normalized consequences of alternatives described in Table 3.3.5 are imported and are each multiplied by their respective weights found in the AHP analysis and in Table 3.3.5's last column. This yields the alternative total, which is the weighted score for each alternative including all criteria. Next, the interdependency tables are imported and all variations of interdependence and alternatives are tested against each other using their alternative value as a score.

Now that all of the combination of alternatives has been compared, the program tabulates the results into a table that includes the alternative numbers in each combination, their alternative value, and a counter that counts the number of combinations. The number of combinations produced by this analysis is 55. This table is then sorted so that the combinations with the highest alternative values are first and continues in the descending order, as shown in Table 3.4.1. This program can only consider interdependence of two alternatives.

3.4 Discussion

Table 3.4.1 is the sorted table from the program, limited to the top ten highest scoring combinations. If the program returns a total score value of 1 or less, the choice is considered to be neutral or less preferable, respectively (Rajabi et al. 1998). Table 3.4.1 shows the ten highest ranked combinations available out of 55 combinations for the aviation industry. A sensitivity analysis can be performed by making a small adjustment to one of the normalized consequence values as shown in Table 3.3.5 and determining if the small change has a large effect. If the values for corn and algae are switched, meaning that the industry prefers a highly subsidized vegetable instead of algae, the program returns the same combination of high bypass engines and algae. However, the total score is now 1.6517 instead of 1.7250, which is a four percent change in score.

Table 3.4.1: Top ten highest scoring alternative combinations

Combination	Alternative 1	Alternative 2	Total Score
1	algae	high bypass engines	1.7250
2	corn	high bypass engines	1.3900
3	corn	algae	1.3794
4	algae	high speed trains	1.0018
5	algae	blended wing	0.9691
6	algae	carbon trading	0.9691
7	high bypass engines	high speed trains	0.9352
8	high bypass engines	blended wing	0.9307
9	algae	retire aging aircraft	0.9265
10	high bypass engines	carbon trading	0.9026

A further sensitivity analysis that could be run is the comparison of the first analysis of this problem versus the iteration shown in this chapter. In the first analysis, AHP was not included and the weights were estimated from statements published by industry leaders. The estimated weights for the previous method are given below:

$$w_{ROI} = 0.4, w_{CO2} = 0.3, w_{min.disrupt} = 0.2, w_{pop} = 0.1$$

$$w_{ROI} > w_{CO2} > w_{min.disrupt} > w_{pop}$$

When these weights were run through the program, they produced the top ten combinations shown in Table 3.4.2 (Karnis et al., 2015b). The order of combinations is different, except for the first three combinations. If the first combination from both methods were compared, the current weights would produce a total score of 1.7250 while the previous weights produce a total score of 1.8536. This is a 7% difference between the results.

Table 3.4.2: Top ten highest scoring combinations of alternatives using a different set of weights

Combination	Alternative 1	Alternative 2	Total Score
1	algae	high bypass engines	1.8536
2	corn	high bypass engines	1.5028
3	corn	algae	1.4950
4	high bypass engines	blended wing	1.0570
5	algae	high speed trains	1.0450
6	algae	carbon trading	1.0100
7	high bypass engines	high speed trains	1.0090
8	algae	blended wing	1.0000
9	high bypass engines	retire aging aircraft	0.9740
10	algae	carbon trading	0.9516

3.5 Summary

According to the preferences and weights inferred from the aviation industry and from the interdependencies between alternatives, it is made clear by the analysis that the most reasonable solution for decision makers in the aviation industry to achieve their goals is the use of high bypass engines and algae biofuel. While both alternatives have high initial investments, they are minimally disruptive to the flow of business, have excellent reductions in CO_2 emissions due to fuel reductions, and are not unpopular. The analysis also returned a total score of 1.7250 for the combination, which indicates that the choice is preferable over the second place combination of alternatives which has a score of 1.3900 between corn biofuels and high bypass engines. The third combination of alternatives has a score of 1.3794 and is the combination of corn and algae biofuels. The similarity between the top two results found using the AHP weights indicate that the choice of a biofuel and high bypass engines is strongly preferred over all other alternative combinations, which is consistent with the fact that the aviation industry has already been investing in these two areas. Customers and environmentalists will also agree with this path because high bypass engines are more efficient than normal bypass engines by 46% (Dray et al., 2010) and algae biofuels use up to 70% of atmospheric carbon that is expelled by the same amount of petroleum (Air Canada, 2014). This combination of alternatives has been shown as the most preferable choice for the aviation industry.

The aviation industry has to consider many financial, political and public opinions before any changes can be implemented. As seen above, the combination of alternatives shown to score highly within a multiple criteria decision making framework that takes into account alternative interdependence using the industry's preferences is to invest in both algae biofuels and high bypass engines and to design them for each other. While this chapter focuses on driving forces for change in terms of environmental sustainability through the aviation sector, it is still uncertain whether or not proposed changes are sufficient to reach GHG emissions reduction targets. An area for further study would be to examine if the chosen alternative would be able to meet the goals agreed to by the industry and ICAO of reducing CO_2 emissions by 50% by 2050 (ICAO, 2014).

Chapter 4. Controversy over the International Upper Great Lakes Study Recommendations

4.1 Introduction

In April 2013, the International Joint Commission released a report on a five year study that was commissioned to investigate the fluctuating water levels in the Laurentian Great Lakes (IJC, 2013). In the same year, the water levels on Lakes Michigan and Huron hit a record low at 175.57 meters (US Army Corps of Engineers, 2014). The IJC's report also incorporated two recent studies from the International Upper Great Lakes Study (IUGLS) Board concerning the impact of the St. Clair River on the Upper Great Lakes water levels and the regulation of Lake Superior's water levels (IUGLS, 2009, 2012). The combined results of these studies led to the recommendations drawn by the IJC in its final report to the Canadian and American governments on April 15, 2013, which included multi-lake water regulation, restoration of Lakes Michigan and Huron water levels, and an adaptive management plan to monitor future water levels. The adaptive management plan was criticized by several local and environmental groups as being an ineffective measure against persistent low water levels in Lakes Michigan, Huron and Superior, or the recent experience of unusually high water level in Lakes Michigan and Huron (Van Brenk, 2014). This Chapter examines the contextual information surrounding the IJC's report released in April 2013 and how the preferences of the decision makers played a key role in determining the most stable scenario for this situation. Some of the research in this chapter is reported by Karnis et al. (2015a).

4.2 Water Levels of the Laurentian Great Lakes

4.2.1 Economic Context

The Laurentian Great Lakes consist of large and complex ecosystems that provide water and means for economic activity to millions of people in the United States and Canada. There are several different groups of people that rely on the ebb and flow of the system's water for their own uses, including those involved in shipping industries, commercial fishing, power generation, manufacturing, recreation and tourism. In 2010, the Great Lakes-St. Lawrence Seaway system directly employed 92,923 people, who received a total of $4.5 billion dollars (CAD) in wages and salary (Martin Associates, 2011). The firms that provide vessel services, cargo handling, and inland transportation services earned $34.6 billion (CAD) in business revenue, which was split almost evenly between the United States and Canada (Martin Associates, 2011). These pursuits are spread out over two Canadian provinces and eight American states that border the system. There are about 73 million tourist visits to the Great Lakes each year and over 100,000 cottage owners on the shoreline (Zebryk, 2013).

However, each of these interested parties can have a strong opinion about the water's use and distribution, which may lead to controversy over the desired water levels. The president of the Canadian Ship Owners Association, Robert Lewis-Manning, confirmed that "we are seeing lower cargo volumes just out of constraint from draft – the amount of water available to a ship – in certain sections of the system" which means that ships cannot carry as much cargo as before, and fortunately "it is nowhere near the point where the bottom line is being seriously impacted" (Brennan, 2012). Hence, controlling water levels may not be of benefit to the shipping industry if it incurs a high cost. On the other hand, Mary Muter, chair of the Sierra Club Ontario's Great Lakes section, advocates for a gradual increase of 25 cm to Lakes Huron and Michigan water levels to compensate for what has been lost over the last 40 years (Mackarael, 2012). Such intervention to restore water levels is supported by observed environmental impacts such as the destruction of wetlands due to lowered water levels. As a vital and finite resource, it seems obvious to environmental groups that water is something worth saving at any cost.

4.2.2 Environmental Context

The controversy is agitated further by the considerable fluctuation of the water levels in the Great Lakes in recent history, as shown in Figure 4.2.1. The Great Lakes have receded to 60 cm below the historic average over the last 80 years (Mackarael, 2012). These fluctuations are caused by anthropogenic factors as well as long-term climate trends and are measured by a standard called IGLD 1985, which is designed to increase the accuracy of water level measurement by comparing a reference location to an elevation reference system based on the movement of the Earth's crust. The standard is adjusted every 25 to 35 years (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1992). When the water levels reach the extremes of the ranges shown in Figure 4.2.1, there can be expensive and detrimental impacts such as loss of beaches due to high water levels and destruction of wetlands due to low water levels (International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013). If the extreme conditions persist for some time, the impact becomes increasingly dire. High water levels can cause flood, soil erosion, loss of wetlands, greater susceptibility to storm damage and economic loss due to flooding of recreational lands. There is also a risk of high channel flows that can impede navigation for industrial shipping (International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013). On the other hand, low water levels can lead to increased dredging to maintain shipping lanes, loss of marina services, shipping delays caused by ships needing to lighten their load, and exposure of mudflats. There is also an increased risk of near-shore water quality issues, loss of hydropower generation and risks to water supply infrastructure (International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013).

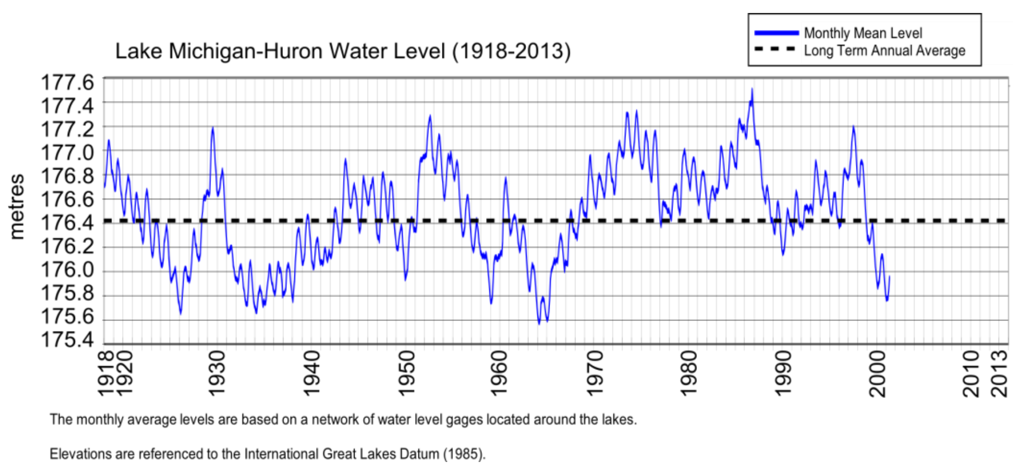

Figure 4.2.1: Water levels on Lakes Michigan and Huron over the historical record (US Army Corps of Engineers, 2013)

4.2.3 Historical Context

In an effort to regulate water levels, the physical systems have been altered by constructing diversions, dams, and locks, by dredging the connecting rivers and by hardening the shore line. There are two main facilities to regulate the water flow throughout the Great Lakes system: the Soo locks located in the St Mary's river connecting Lake Superior to Lake Huron near St. Mary's Falls Canal, and the Welland Canal connecting Lake Erie to Lake Ontario and traversing the Niagara Peninsula (Chamber of Marine Commerce, 2014). The St. Clair River has been dredged to make it deeper and wider so that commercial shipping may have easier access to the city of Detroit through Lake St. Clair and to the Atlantic Ocean via the St. Lawrence River (Mackarael, 2012). The locks and canal are controlled water drainage points, whereas the St. Clair River is largely uncontrolled. These locations can be seen in Fig. 4.4.2. The arrows indicate the direction of water travel.

Figure 4.2.2: A map of the Laurentian Great Lakes and main drainage points

Fluctuating water levels is an issue that has been studied many times by the IJC since the early 1960’s. The IJC is mandated by the Canadian and United States governments to resolve disputes between the two countries under the Boundary Treaty Waters Act of 1909 and regulates projects affecting boundary waters (IJC, 2013). The most notable studies in this time are listed in Table 4.2.1. The most recent study, titled the "International Upper Great Lakes Study", has created considerable controversy among interest groups about what is to be done about fluctuating water levels.

Table 4.2.1: Studies by the IJC concerning water levels (The International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013)

Year	Study
1964 – 1973	Regulation of Great Lakes Water Levels Reference Study
1977 – 1981	Great Lakes Diversions and Consumptive Uses Reference Study
1977 – 1983	Limited Regulation of Lake Erie Study
1987 – 1993	Water Levels Reference Study
1999 – 2000	Report on the Protection of Waters of the Great Lakes
2001 – 2006	Lake Ontario–St. Lawrence River Study
2007 - 2012	International Upper Great Lakes Study

4.2.4 Cooperative Context

Although the interest groups in this study have different priorities, there is a meaningful reciprocal arrangement between them that should not be overlooked. The environmental groups rely on the local populace for support and the local populace relies on the shipping industry to provide economic stimulus to the area. These groups are consulted by the IJC, as well as the IJC's commissioned scientists (IJC, 2013). However, these multiple interest groups each work to achieve their own objectives, which can result in a lack of cooperation that seriously hinders dialogue between groups. This lack of voluntary cooperation as well as enforceable cooperation between groups means that the conflict must be modeled as a non-cooperative game with an appropriate method like the graph model for conflict resolution (GMCR) methodology (Fang et al., 1993; Kameda et al., 2012).

In the next sections, the controversy over the recommendations is investigated by modeling and analyzing the conflict with the graph model for conflict resolution in order to gain insights on why the public reacted negatively to the IJC report and whether there are pathways to improve public perception by influencing the conflict towards win-win resolutions for all interested parties.

4.3 Modeling: Decision Makers, Options and Preferences

On April 15th 2013, the IJC released a report to the Canadian and United States governments containing their advice on the Recommendations of the International Upper Great Lakes Study (IJC, 2013). The report was based on the findings of a technical study performed by the International Great Lakes Study Board which determined possible impacts of climate change and water variability on water levels in the Great Lakes. The study concluded that an active management plan and team was the only necessary solution to the water level problem, which would consist of active monitoring of water levels and the option to revisit the issue in the future (The International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013).

There were public outcries from several stakeholders before and after the report was released. Many who lived, worked, and played on the Great Lakes felt that the recommendation from the IJC did not agree with their values, the objectives of which are mainly to protect the lakes environmentally and to keep the water levels steady so that business is not interrupted (Porter, 2012). Shlozberg et al. (2014) estimate a cost of $18.82 billion (CAD) by 2050 due to low water levels in the Great Lakes. In particular, the greatest economic impact will be to commercial fishing and recreational boating at $12.86 billion (CAD) (Schlozberg et al., 2014). The vice-chair of Restore Our Water International also agrees that the environmental effects are significant; for example, the increased drainage from the St. Clair River and other sources causes less dilution of fertilizer and other pollutants resulting in large algae blooms (Desjardins, 2013).

Given the significance of the IJC's role in making recommendations to both Canada's and the United States governments, the publishing of its advice on the recommendations of the International Upper Great Lakes Study (IJC, 2013) is a key event in this conflict's pathway to resolution. Hence, the point in time chosen to analyze the conflict among different parties in how to manage the water level of Lakes Michigan and Huron and Georgian Bay is just prior to the release of the IJC Report on April 15th 2013.

4.3.1 Decision Makers and Options

It is crucial to the integrity of the analysis to properly identify the decision makers. For this case, the groups most directly affected by the changing water levels would be the house or cottage owners and businesses living in and around the Great Lakes. These people would have a strong preference for keeping the water levels at their historical average so that their housing values, industry, fishing and general recreation are undisturbed. Property owners advocate their position through groups that require property ownership in the Great Lakes area, like the Georgian Bay Association and the Federation of Ontario Cottagers' Association. Conservationists are concerned about the effect that water levels would have on the environment and have formed many environmental groups advocating for water levels consistent with the historical average, such as Great Lakes United and Lake Huron Center for Costal Conservation (Zebryk, 2013) Another interested group consists of the shipping industries that use the Great Lakes-St. Lawrence Seaway to transport oil and other goods (Zebrek, 2013). This group has an economic interest in keeping the water levels consistent, but has no interest in returning them to historical levels. Finally, the International Joint Commission is a neutral body comprised of members from the USA and Canada that is mandated to protect the shared waterways and to regulate shared water issues in an objective manner.

The main DMs involved in the conflict before the IJC report was released can be categorized into three main groups: Local DMs, Shipping DMs and the IJC. The Local DMs would like there to be some intervention by the governments to return water levels to the historical average and stabilize them at that desired level, the Shipping DMs would like there to be no costly intervention because there is little for them to gain from one. Finally, the IJC is interested in coming to objective and scientifically sound recommendations for the governments of Canada and the United States to consider. In this study, the Local DMs consist of municipalities, local industries, and cottagers. The Shipping DMs in this conflict are the oil and shipping industries, which have an economic preference for the current water levels so that they will not need to alter shipping routes or equipment and ports (Zebrek, 2013). The IJC is by mandate neutral between the Canadian and American governments and is also mandated to find the best international solution. The decision makers identified and their options are given in Table 4.3.1.

Table 4.3.1: Decision makers and their options

Decision Maker	Option	Description
Local DMs	1. Protest publicly	If the Local DMs feel that their needs are not being represented, they can protest publicly in the form of demonstrations and through the media.
Shipping DMs	2. Reduce shipping via Great Lakes	If the Shipping DMs feel that the cost burden is too great to transit through the Great Lakes, they can substitute marine shipping with another transportation mode.
IJC	3. Recommend a permanent solution	A permanent solution would be a series of locks, a canal, or speed bumps at one of the major uncontrolled drainage points like the St. Clair River. Requires a large investment from both governments in terms of time, money and other resources.
	4. Recommend a temporary solution	A temporary solution needs a much smaller investment than a permanent solution, but still requires the approval of both nations because it affects them both. It would provide a short-term solution to fluctuating water levels. A temporary solution would be the use of large floating buoys to displace water and temporary structures in the St. Clair River.
	5. Recommend active management	An active management solution would be to wait, watch and determine if there is enough evidence to support the implementation of a permanent or temporary solution.

4.3.2 Current Preferences

There are 16 feasible states as shown in Table 4.3.2. State 2 is known as the status quo state, or the state of the decision makers' positions before the game is started. In this state, the Local DMs are protesting publicly as a way to influence change in the management of the water levels while the Shipping DMs have not reduced shipping on the Great Lakes and the IJC has not made any recommendations yet.

Table 4.3.2: Feasible states

	States															
Option Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Local DMs																
1. Protest	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
Shipping DMs																
2. Reduce	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
IJC																
3. Permanent	N	N	N	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N
4. Temporary	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	N	N	N
5. Active Management	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y

The preferences for each DM are described in Table 4.3.3. This table uses the option numbers from Table 4.3.1 and a series of prioritized logic statements to specify the nature of the preference. The resulting ordinal ranking of states according to each DM's preferences is listed in Table 4.3.4.

There are three possible methods of ascertaining ordinal preferences for this problem. They are option weighting, option prioritization, and fine tuning (Fang et al., 2003a) Option weighting involves ranking the states by assigning weights to options and using total weights. Option prioritizing is where a set of lexicographic preference statements is obtained for each decision maker. The preference statements are ordered by placing the statements that have the highest priority in determining a decision maker's preferences at the top and decreasing the priority of the statements as the set continues. An algorithm is utilized to rank the states from the most preferred to the least preferred (Fang et al., 2003a). Fine tuning, or direct ranking, is a method where the preferences of a decision maker are ranked individually with higher preference first. This method is often used with option weighting to include more complexity in the model as represented by the situation (Fang et al., 2003a). The option prioritization method is used in this study to rank the states from the most preferred to the least preferred.

Table 4.3.3: Prioritized preference statements for all decision makers

Decision Maker	Preference Statement	Explanation
Local DMs	3	From this perspective, a permanent solution would return water levels to the historical average.
	1 IFF 5	Local DMs will protest if active management is recommended.
	4	A temporary solution would also be preferred over no solution as it also provides some stability (albeit in a short-term way).
	-5	An active management solution has been deemed unacceptable to many activist groups (Desjardins, 2013).
	-2	The city and local industries do not want to impede the shipping industry.
Shipping DMs	5	The current set up of docks, shipping lanes and canals is profitable for the oil and shipping industry. Therefore, they would prefer the solution that does not disrupt shipping and is the least expensive: active management.
	2 IFF 3	If shipping in the Great Lakes were to become too expensive, i.e. more than $3.6 billion CAD in transportation costs a year (St. Lawrence Seaway Management Corporation, 2012), the goods could be shipped over land.
	4	However, a temporary solution costs less than a permanent one, which means less taxes and toll increases.
	-3	Shipping DMs would prefer to not have a permanent solution due to shipping disruptions and increased tolls.
	-1	They would like to remain on friendly terms with the cities to prevent business disruptions.
IJC	5	The IJC has a preference for an active management solution because the IUGLS found that the water levels are adequate and consistent enough to not require immediate action (IUGLS, 2012).
	4	A temporary solution is preferred over a permanent one because its study shows that the water levels do not require drastic action (IUGLS, 2012).

	-1, -2	The IJC is tasked with finding an objective solution to the problem without thought to the opinion of other stakeholders, but as a government-sponsored commission, it must have a slight preference for the welfare of citizens over that of the commercial industry.
	3 IFF 1 & 2	A permanent solution with the support of the public and industry is slightly preferred over its singular opinions due to the collaborative mandate of the IJC.

Table 4.3.4: Ordering of states based on DMs' preferences from most preferred to least preferred states (left to right)

	←Most Preferred State															**Least Preferred State →**
Local DMs	5	7	6	8	9	11	1	3	14	16	10	12	2	4	13	15
Shipping DMs	13	14	15	16	9	10	1	2	7	8	11	12	3	4	5	6
IJC	13	15	14	16	9	11	10	12	1	5	3	7	2	6	8	4

4.4 Analysis: Static Stability, Status Quo Analysis, and Pareto Optimal States

A state is considered an equilibrium if it is a state where none of the decision makers are motivated to move to another state based on a defined solution concept. Using decision support system GMCR II (Fang et al., 2003a,b), only states 14 and 16 are found to be equilibria. In both equilibria, the public protests while the IJC recommends active management. They are only differented by the reaction of the Shipping DMs, whereas in state 14 the Shipping DMs maintain the status quo, in state 16 the Shipping DMs decide to reduce shipping through the Great Lakes. State 14 is considered a strong equilibrium based on Nash stability (R), general metarationality (GMR), symmetric metarationality (SMR), sequential stability (SEQ), and nonmyopic stability (NM). On the other hand, State 16 is a weak equilibrium because it is found to be an equilibium only by GMR and SMR solution concepts. Relative to decision makers' preferences, states 14 and 16 are highly preferred states for Shipping DMs and the IJC and in the lower end of the spectrum for the Local DMs.

Table 4.4.1 shows a status quo analysis, where it can be seen that state 14 is reachable from the status quo of state 2 simply by IJC making a unilateral improvement from state 2 to state 14. On the other hand, state 16 is not reachable from the status quo because it would require the Shipping DMs to disimprove its position unilaterally either from state 14 to move to state 16 or from state 2 to state 4. As a result, state 14 is the most likely resolution of the modeled conflict.

Table 4.4.1: Status quo analysis

	Status Quo						Status Quo				
	2	✓	14	✗	16		2	✗	4	✓	16
Local DMs											
1. Protest	Y		Y		Y		Y		Y		Y
Shipping DMs											
2. Reduce	N		N	→	Y		N	→	Y		Y
IJC											
3. Permanent	N		N		N		N		N		N
4. Temporary	N		N		N		N		N		N
5. Active management	N	→	Y		Y		N		N	→	Y

Pareto optimal states are states in which it is not possible for a DM to make an improvement without making another DM worse off (Airiau and Sen, 2006). Figure 4.4.1 shows the graph representation of the conflict where the vertices denote states and the edges represent allowable state transitions. In this model, state transitions are reversible, hence a DM can move in both directions of an edge. An arrow denotes a unilateral improvement for the DM that controls the transition as well as an improvement for other DMs. State transitions that would make at least one DM worse-off do not have an arrow head. Starting from the status quo state, unilateral improvements where all DMs improve are marked. From the graph, the Pareto optimal states that are reachable from the status quo state are vertices that have at least one arrow directed into the vertice and no arrows leading out. Hence, states 9 and 14 are Pareto optimal states.

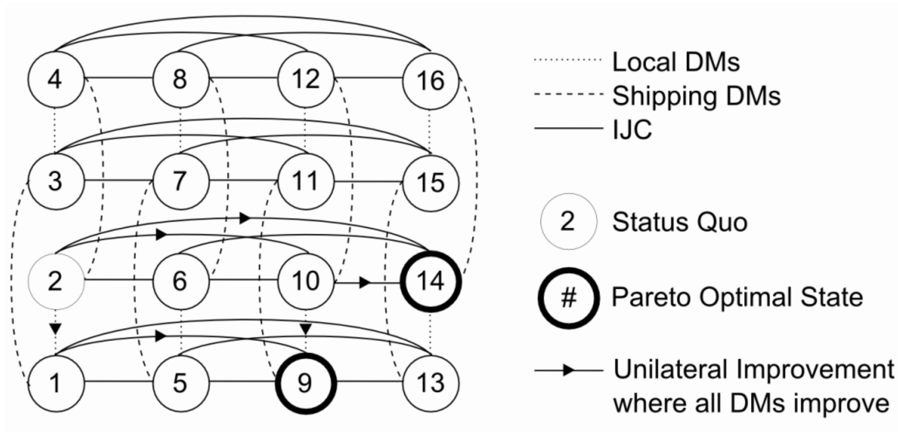

Figure 4.4.1: Pareto optimal analysis using the graph representation of the conflict

4.5 Inverse GMCR Analysis

From the analyses discussed in Section 4.4, it appears that state 14 is Pareto optimal and reachable from the status quo. However, while it is Pareto optimal, it may not be the state that offers the most compromise for all participants. To complete this analysis, a decision support system called GMCR+ was used, which can determine what the movement the decision makers' preference rankings needs to be to achieve a specified outcome (Kinsara et al., 2015a). Once the states and preferences that lead to a particular outcome are found, it becomes easier for a mediator to influence the result of the conflict (Kinsara et al., 2015b). When the IJC decides to make a decision, it can move from the status quo (state 2) to states 10 or 14, where it chooses an active management or temporary solution. If the IJC chooses to move to state 10 from the status quo, the Local DMs can move from state 10 to state 9 by choosing not to protest, which is a probable outcome of this move. If the IJC chooses to move to state 14, the path to state 16 is through the Shipping DMs' choice to reduce traffic. State 9 offers more compromise in this situation than state 16 because it aligns with the priorities of the Local DMs and the Shipping DMs, whereas state 16 would cause a negative reaction from both decision makers.

This observation leads to the question of which preferences could be changed to promote compromise between the decision makers. If the desired equilibrium for the inverse analysis is set to state 9 and the inverse GMCR function of the GMCR+ program is run, it returns which preferences must be changed for each decision maker to achieve the desired result. If equilibrium at state 9 is to be achieved, the Local DMs must prefer state 9 over state 10, which is the case as shown in Table 4.3.4. The Shipping DMs must prefer state 9 over state 11, which is confirmed by an inspection of Table 4.3.4. The IJC must also prefer state 9 over the states 2, 5, and 13, where state 2 is the status quo, state 5 is the use of a permanent solution with no protests or shipping reductions, and state 13 is the use of an active management solution without protests or shipping reductions. As shown in Table 4.4.3, the IJC prefers state 9 over state 2 and state 5. However, the IJC will need to shift its preference from state 13 over state 9 to state 9 over state 13. According to its commissioned study, there is not enough evidence to choose a temporary solution over an active management solution. If there was enough scientific evidence to suggest the change, there is reason to believe that the IJC would be more open to a temporary solution. To find such evidence to change its position, there must be scientific studies carried out that may support the implementation of temporary or permanent solution.

4.6 Discussion

The stability, status quo and Pareto optimal analyses show that the most likely resolution to the conflict is state 14, where the IJC recommends that the governments of Canada and the United States implement an active management solution to manage the water levels in the Upper Great Lakes, the Shipping DMs do not reduce shipping traffic in the Great Lakes-St. Lawrence Seaway, and the Local DMs protest publicly. Indeed, Local DMs continued to protest publicly through statements in newspaper articles that appeared shortly after the IJC report was released. Headlines such as "Activists denounce inaction on Great Lakes' low water 'crisis'" appeared on April 18, 2013 (Desjardins, 2013) and "It will take all our efforts to restore the Great Lakes" appeared on July 3, 2013 (Nies, 2013). If the IJC had hoped to reduce protests by Local DMs which play a role in shaping public perception, the IJC would need to assuage fears that the water levels will continue to decrease. This could perhaps be achieved by publishing counter-argument articles in newspapers and other media on the reasons why an active management solution is best and backed by sound science to support its conclusions. Its findings will have to be presented in a format that is more accessible and intuitive than the documents outlining its recommendations to the Canadian and American governments. The status quo analysis further confirmed that state 14 is the likely resolution to the conflict since the only other equilibrium is not reachable via unilateral improvements from the status quo.

The search for Pareto optimal states was undertaken to find pathways towards possible win-win resolutions. As it turns out, state 14 is a Pareto optimal state. From the perspective of the Local DMs, state 14 is generally not considered a win. However, the analysis also revealed state 9, where IJC recommends a temporary solution and this recommendation is essentially supported by both Local and Shipping DMs. While this state is less preferred than state 14 for both IJC and Shipping DMs, it is a compromise which is much more satisfying for Local DMs than when compared to the status quo and active management solutions. As an evolutionary resolution, a temporary solution could be argued as a reasonable and reachable compromise, however, not a win-win. The inverse GMCR analysis shows that state 9 is reachable by the cessation of protests by the Local DMs if the IJC chooses a temporary solution. However, the IJC would have to adjust its preferences so that its desire to implement an active management solution without protests or a reduction in commerce is not so inflexible. It may take a large outreach from the public or new scientific evidence of water level fluctuation to sway its opinion. Consequently, it should be noted that state 9 may not appeal to Local DMs with extremist perspectives and who are not willing to compromise.

4.7 Summary

This chapter has examined the circumstances and participants in a situation that led to a controversial recommendation being submitted to the Canadian and American governments. It was found that there were three main groups of DMs: the Local DMs, who advocated for a permanent solution to restore water levels to the historical average, the Shipping DMs who generally do not wish to face business disruptions, and the IJC, which was tasked with recommending an objective solution to the involved governments. The model was found to produce results that reflected the real-world conflict. The most likely resolution to the modeled conflict is an active management solution recommended to the governments where Local DMs continue to protest and Shipping DMs maintain shipping traffic. Further discussion determined that this state was both reachable through status quo analysis and further strengthened by Pareto optimality. However, Pareto optimal analysis also revealed an alternative future in which a temporary solution is recommended, representing a compromise rather than a win-win resolution unfortunately. Arguably, however, it may be in the best interests of all parties and help to nurture collaboration by taking action towards preserving the environmental integrity of the Great Lakes without causing undue difficulties to any participant. The IJC appears to be the most resistant DM to this compromise because of its strong preference for an active management solution over a temporary one. This model and analysis indicates that this goal is not only possible, it is attainable. An opportunity for further study would be an analysis of the conflict after the IJC published its report, thereby changing to role of the IJC from a DM role to a support role, and how the Canadian and American governments enter the study as decision makers.

Chapter 5. Conclusions

5.1 Summary of Contributions

This thesis studies two different types of decision making situations in order to clarify and understand the underlying values and considerations that have led to the decision making behavior on the part of the participants so that insights on creating movement towards desired outcomes is revealed. The first study on Evaluating Actions towards Sustainable Aviation investigates possible actions by the aviation industry in order to reduce emissions and add value to its business model. For the perspective of the overall goal, this problem is found to be a single participant-multiple criteria (SPMC) decision problem that is simplified from a multiple participant-multiple criteria decision problem because of the decision to represent the aviation industry as one decision maker. The study determines which alternatives would be the most beneficial for the aviation industry as a whole, with a focus on the interdependence between alternatives. It is found that the use of a combination of high bypass engines and algae biofuel would be the best choice out of the presented alternatives, which coincides with opinions of major industry players as specified by public releases and research projects. This analysis provides value outside the problem because it shows a method of considering interdependence between alternatives in multiple criteria decision making problems.

The second study on Controversy over the International Upper Great Lakes Study Recommendations is a conflict in nature, with three decision makers struggling against each other. The Local DMs want a permanent solution to the fluctuating water levels, while the Shipping DMs prefer a solution that does not impede trade and the IJC decides on an active management solution based on its own scientific studies. This problem initially is an MPMC decision problem, but is simplified into a multiple participant-single criterion (MPSC) decision problem. This simplification could be carried out because each participant has to form its own preferences over possible states based on its own set of criteria. The decision by the IJC causes significant strife among the local people, who feel that the solution is inadequate for their needs. A continued analysis of the situation reveals a solution that is more of a compromise for all parties, but would take a significant change in preferences from the IJC to make it a realistic solution. The inverse analysis that describes what preferences needed to change for a more amiable solution is of particular value. This method of looking at a result and determining what need to change to come to that solution is valuable because it provides insight into what steps are needed to influence stakeholder values and opinions, which is invaluable for encouraging compromise and mutual satisfaction in the solution. These two studies turn out to be very different problems that require different approaches and solution methods, which gives value to this thesis by providing a more varied experience on the applications of multiple participant-multiple criteria decision making.

5.2 Future Work

There are several avenues for expanding this work in the future. For the sustainable aviation study, an AHP analysis was performed to determine the stakeholder preferences, however there was limited sensitivity analysis performed. An extensive sensitivity analysis would determine if the solution is robust and ready for implementation. The program could also be improved so that it could handle interdependence of more than two alternatives in its analysis so that a more comprehensive analysis could be performed.

For the Great Lakes study, the analysis of the inverse GMCR that identified which preferences would need to change to move the solution from a solution with one unhappy party to more of a compromise could be expanded to include which policies the IJC would need to reconsider so that its preferences could be changed from state 13 over state 9 to state 9 over state 13. However, the analysis of its policies and motivations would have to include an extensive review of its policies and scientific studies. Both studies were completed without input from any stakeholders besides statements issued in newspaper articles and public releases. The analysis would be more accurate if the stakeholders were available for consultation to clarify their motivations, opinions and preferences. However, it may be difficult to convince some stakeholders to divulge their opinion as the information may be considered sensitive for a report that will be published. Aviation is a highly competitive industry where one participant may not feel that revealing the details of its sustainability strategy to its competitors is the best business strategy.

There are several ways to improve the analyses above, but the studies are of sufficient detail and context to produce accurate and implementable results. Their accuracy can be defended by public statements released by stakeholders in the aviation industry that concurs with the result of the Sustainable Aviation study. The accuracy of the Great Lakes study is also verified by the implementation of the IJC decision where an action management solution is used while shipping continues and the local populations protest in 2013. Hopefully these analyses provide some clarity on the motivations and process of multiple participant-multiple criteria decision making for some actual issues that are relevant in the world today.

Appendix A: Interdependence Ratios of Alternatives for Criteria

Table A.1: Interdependence ratios for ROI

	corn	*algae*	*engines*	*blended wing*	*reduce altitude*	*formation flying*	*descent*	*ground vehicles*	*aircraft*	*carbon trading*	*trains*
corn	0	0	0.2	0	0	0	0	0	0	0	0
algae	0	0	0.4	0	0	0	0	0	0	0	0
high bypass engines	0.2	0.4	0	0	0	0	0	0	0	0	0
blended wing	0	0	0	0	0	0	0	0	0.1	0	0
reduce altitude	0	0	0	0	0	0	0	0	0	0	0
formation flying	0	0	0	0	0	0	0	0	0	0	0
constant descent	0	0	0	0	0	0	0	0	0	0	0
electrical ground vehicles	0	0	0	0	0	0	0	0	0	0.1	0
retire aging aircraft	0	0	0	0.1	0	0	0	0	0	0.2	0
carbon trading	0	0	0	0	0	0	0	0.1	0.2	0	0.1
high speed trains	0	0	0	0	0	0	0	0	0	0.1	0

Table A.2: Interdependence ratios for CO_2

	corn	*algae*	*high bypass engines*	*blended wing*	*reduce altitude*	*formation flying*	*constant descent*	*electrical ground vehicles*	*retire aging aircraft*	*carbon trading*	*high speed trains*
corn	0	0.7	0.6	0	0	0	0	0	0	0	0
algae	0.7	0	0.8	0	0	0	0	0	0	0	0
high bypass engines	0.6	0.8	0	0.4	0	0	0	0	0	0	0
blended wing	0	0	0.4	0	0	0	0	0	0	0	0
reduce altitude	0	0	0	0	0	0	0	0	0	0	0
formation flying	0	0	0	0	0	0	0	0	0	0	0
constant descent	0	0	0	0	0	0	0	0	0	0	0
electrical ground vehicles	0	0	0	0	0	0	0	0	0	0	0
retire aging aircraft	0	0	0	0	0	0	0	0	0	0	0
carbon trading	0	0	0	0	0	0	0	0	0	0	0
high speed trains	0	0	0	0	0	0	0	0	0	0	

Table A.3: Interdependence ratios for minimal disruptions

	corn	*algae*	*high bypass engines*	*blended wing*	*reduce altitude*	*formation flying*	*constant descent*	*electrical ground vehicles*	*retire aging aircraft*	*carbon trading*	*high speed trains*
corn	0	0	0	0	0	0	0	0	0	0	0
algae	0	0	0	0	0	0	0	0	0	0	0
high bypass engines	0	0	0	-0.5	0	0	0	0	0	0	0
blended wing	0	0	-0.5	0	0	0	0	0	0	0	0
reduce altitude	0	0	0	0	0	0	0	0	0	0	0
formation flying	0	0	0	0	0	0	-0.5	0	0	0	0
constant descent	0	0	0	0	0	-0.5	0	0	0	0	0
electrical ground vehicles	0	0	0	0	0	0	0	0	0	0	0
retire aging aircraft	0	0	0	0	0	0	0	0	0	0	0
carbon trading	0	0	0	0	0	0	0	0	0	0	0
high speed trains	0.2	0.2	0	0	0	0	0	0	0	0	0

Table A.4: Interdependence ratios for popularity

	corn	*algae*	*high bypass engines*	*blended wing*	*reduce altitude*	*formation flying*	*constant descent*	*electrical ground vehicles*	*retire aging aircraft*	*carbon trading*	*high speed trains*
corn	0	0.2	0	0	0	0	0	0	0	0	0
algae	0.2	0	0	0	0	0	0	0	0	0	0
high bypass engines	0	0	0	0.3	0	0	0	0	0.1	0	0
blended wing	0	0	0.3	0	0	0	0	0	0	0	0
reduce altitude	0	0	0	0	0	0	0	0	0	0	0
formation flying	0	0	0	0	0	0	0	0	0	0	0
constant descent	0	0	0	0	0	0	0	0	0	0	0
electrical ground vehicles	0	0	0	0	0	0	0	0	0	0	0
retire aging aircraft	0	0	0.1	0	0	0	0	0	0	0	0
carbon trading	0	0	0	0	0	0	0	0	0	0	0.1
high speed trains	0	0	0	0	0	0	0	0	0	0.1	0

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