# An Evaluation of the Economic Impact of Proposed Non-Indigenous Species Control Measures for the St. Lawrence Seaway Using Multi-Attribute Decision Theory

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## ABSTRACT

Mandatory ballast water management resulting in an increase of required freight rates (RFR) on the St. Lawrence Seaway might bring modal shifts from the marine transportation mode to other modes. The modal shifts will possibly bring several side effects, such as worse air pollution, lower transportation safety etc. To evaluate the trade off between these side effects and the ballast water management effects, a multi-attribute decision problem needs to be solved. This paper uses the Analytical Hierarchy Process (AHP) method, fuzzy set theory, and utility theory to analyze the above multi-attribute optimization problem. A numerical example is presented in this paper. The results indicate that such modal shifts should be avoided, since the less cargo is shifted from the marine mode to other modes, the more favorable the alternative is.

*Keywords: utility theory; non-indigenous species; modal shift; analytical hierarchy process; fuzzy set theory*

## 1. Introduction

The unintentional introduction of non-indigenous species (NIS) into ports and waterways around the world may have already caused substantial economic and ecological problems for those countries with marine trade (National Research Council (NRC), 1996). It is estimated that three individual aquatic organisms (the Zebra Mussel, the Asian Clam, and the Green Crab) alone result in the costs about $4 billion each year (Mackey et al., 2000).

Ballast water is recognized internationally as a vector for the introduction of invasive marine organisms. Since the 1970s, ballast water has received considerable attention (NRC, 1996; Oemcke, 1999; Parsons et al., 1997, 1998; Mackey et al., 2000; Hay et al., 1998). An international research and regulation effort has evolved since the mid-1980s (International Maritime Organization (IMO), 1997), which has identified some management methods for controlling species introductions via ballast water. One of the most significant results of this effort has been the development of national and international regulations to control the movement of ballast water (State of California, 1999; State of Washington, 2000; United States Coast Guard, 1999; United States Congress, 1996; IMO, 1997, 1998). Several countries, including the United States, have unilaterally introduced controls, and the IMO (1997) is in the process of introducing international controls on ballast water.

The economic impact of mandatory ballast water treatment on the Great Lakes shipping industry is very important, since a possible increase in the marine freight rates due to the mandatory requirement may cause modal shifts from the marine transportation mode to other transportation modes. If such modal shifts occur, they may bring several side effects such as increased air pollution, decreased transportation safety, reduced fuel efficiency and increased noise pollution as Thorp (1993) has shown

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in his research. These side effects would affect society as a whole.

In order to get the best result from the regulation of NIS control, the legislative body has to balance prevention and control of non-indigenous species against overall cost to the economy and society. This is definitely a multi-attribute decision problem.

In this paper, we will model the decision problem for the legislative body as a multi-attribute decision problem, and use the AHP method, utility theory, and fuzzy set theory to solve it. In section 2, a literature review is given. In section 3, methods to solve the multi-attribute decision problem are discussed. In section 4, a numerical example is presented. In section 5, conclusions are drawn.

## 2. Literature Review

There are many references in the literature related to the NIS problem (NRC, 1996; Oemcke, 1999; Parsons et al., 1998; Mackey et al., 2000; Hay et al., 1998). However, few articles focus on the economic impact of the possible increase of the Required Freight Rate of the marine transportation mode on the shipping industry and related side effects such as environment pollution and transportation safety.

Parsons et al. (1997) have finished a preliminary cost analysis of filtration treatment systems. They claim that the economics of a ballast filtration installation is dominated by the capital cost. The average RFR increase will be huge if without government incentive zero interest loan. Once the increase of RFR leads to the increase of freight rates, modal shifts will possibly occur.

A possible modal shift may bring several side effects such as an increase in fuel assumption, an increase in transport related fatalities and injuries, and an increase in noise and atmospheric pollution, according to Thorp (1993) and Lambert (1997). Lambert (1997) attempts to place a dollar value on the environmental impact of a modal shift. By comparing the fuel efficiency of the marine mode to those of truck and rail modes, and the air emissions from burning additional fuel to move the same tonnage, Lambert (1997) finds that "waterborne transportation has an environmental cost impact of one fifth that of rail and one tenth of truck". However, he does not provide dollar estimates for the damage caused by accidents for each mode. Through shifting selected waterborne commodity movements to alternative rail and truck modes, Thorp (1993) assesses the comparative energy usage, emission impacts and safety risks of each transportation mode in relation to others. His research shows that vessel transport on the Great Lakes and St. Lawrence River is safer, uses less fuel and produces fewer emissions than either rail or truck when compared with equivalent commodity hauls. However, Thorp (1993) develops examples assuming that there is a marine to rail or marine to truck shift of X million tons annually. A better way is to determine to what extent modal shifts (expressed by X million ton annually) may occur by using multi-attribute decision theory.

Hickling Corporation (1996) shows the economic impact of marine initiatives on the Canadian marine shipping industry. Many factors, other than ballast water treatment, are included in their research. Hickling firstly makes a set of quantitative assumptions on each marine initiative, then incorporates them in a database including 1,240 flows that represent 88% of all marine traffic in Canada. Hickling examines the impact of several proposed marine initiatives on each of the major productive sectors of the Canadian economy that use marine transport. For each sector, one or more case studies are performed. In each case study, a disruption, which means the cargo owner in the case will cease his cargo transportation, or a diversion, which means the cargo owner in the case will divert his cargo to other routes, or more likely other transportation modes (a modal shift), is predicted. However, in this study, no ballast water treatment related costs are included. Hickling's method to determine a modal shift does not take advantage of decision theory.

Several methods can be used to solve the multi-attribute decision problem for the decision analysts, such as the Analytical Hierarchy Process (Saaty, 1980; Yager, 1978; Triantaphyllou, 2001; Sinuany-Stern et al., 2000; Millet and Saaty, 2000; Nolloju, 2001), utility theory (Thurston and Carnahan, 1992; Guyot and Nikolaidis, 1997; Otto and Antonsson, 1993), fuzzy set theory (Thurston and Carnahan, 1992; Guyot and Nikolaidis, 1997; Park, 1987) or combinations of the above methods (Yager, 1978).

The Analytical Hierarchy Process developed by Saaty (1980) is very popular in current decision analysis field, although its validity becomes the topic of a debate due to rank reversals (Triantaphyllou, 2001; Millet and Saaty, 2000). Triantaphyllou (2001) presents two new categories of ranking irregularities when using the AHP method. The first ranking irregularity may occur, if all alternatives are compared two at a time and also simultaneously. The second ranking irregularity may occur as a logical contradiction, failure to follow the transitivity property. Using random data to construct imaginary decision problems, Triantaphyllou (2001) tries to find the frequency of irregularities occurring in multi-criteria decision problems. He concludes that the number of alternatives will play a prime role, while the number of criteria is not important. More alternatives will produce more irregularities. Two reasons, required normalization and the use of an additive function, cause the irregularities in the AHP method. Instead of using the original AHP method presented by Saaty (1980) and the revised AHP method presented by Belton and Gear (Triantaphyllou, 2001), Triantaphyllou (2001) suggests to use a multiplicative AHP method in the final stage of the original AHP method. Under this approach, relatively dimensionless results are used.

$$R(\frac{A_K}{A_L}) = \prod_{j=1}^{n} (\frac{a_{Kj}}{a_{L_j}})^{w_j}$$

where $A_K$ is the K-th alternative,

$A_L$ is the L-th alternative,

$a_{kj}$ is the performance value of the k-th alternative with respect to the j-th criterion in the decision matrix,

$a_{lj}$ is the performance value of the l-th alternative with respect to the j-th criterion in the decision matrix,

$W_j$ is the weight of the j-th criterion.

This method guarantees that the transitivity property holds and the first irregularity will not occur, although it does not guarantee that it will eradicate all of the possible irregularities (Triantaphyllou, 2001). Vargas (1990) has shown that above multiplicative composition gives rise to invalid answers to problems for which the true values are known.

As many papers (Triantaphyllou, 2001; Vargas, 1990) have criticized, the AHP method may not preserve rank, although in some cases rank reversals are valid. Two synthesis models, "Distributive" model allowing rank reversal and "Ideal" model preserving rank respectively, are presented by the researchers (Millet and Saaty, 2000). "Distributive" model normalizes alternative scores under each criterion so that their sum is equal to 1. "Ideal" model divides alternative scores by the score of the best alternative under each criterion. The main difference between two models exists in the preference scoring. In "distributive" model, the preference of an alternative is determined by comparing the alternative with other alternatives. In contrast, "ideal" model compares an alternative to the best alternative under each criterion. Millet and Saaty (2000) propose the following selection guidelines to determine which model to be used:

- When the decision maker is concerned with the extent to which each alternative dominates all other alternatives under the criterion, "distributive" model should be used.
- When the decision maker is concerned with the relative performance of an

alternative to a fixed benchmark, "ideal" model should be used.

Hurley (2001) presents an approach preserving existing rank order in the AHP method. For a pariwise comparison matrix $A=[a_{ij}]$, Hurley (2001) uses the following transformation: $\overline{A}=[a_{ij}^{\alpha}]$. Denote $w_i$ as the eigenvector associated with the maximum eigenvalue of the primitive matrix, and $\overline{w_i}$ as the eigenvector associated with the maximum eigenvalue of the transformed matrix. If $w_i > w_j$, then $\overline{w_i} > \overline{w_j}$ (Hurley, 2001). This property preserves the rank order of alternatives. With the increase of $\alpha$, the relative weight of the alternative with the highest weight will increase and those of other alternatives will decrease. With the decrease of $\alpha$, the relative weights will get closer. The consistency of the pairwise comparison matrix will decrease with the increase of $\alpha$. If a rank order exists in the alternatives, this method preserves the rank order. This approach is useful for sensitivity analysis of a pariwise comparison matrix.

The subjective assessment of the pair comparison matrix in the AHP method also might cause problems. Sinuany-Stern et al. (2000) suggest that the DEA method be used to produce the pair comparison matrix. They claim that no subjective assessment of a decision maker is involved if the DEA/AHP combination is used. Rank reversals also exist in some cases as other papers (Triantaphyllou, 2001; Millet and Saaty, 2000) have pointed out. For the single input and single output, the DEA/AHP and DEA are compatible. However, it is not true for the multiple inputs and outputs. One restriction for the application of the DEA/AHP method is that it requires the precise output and input. Once the alternatives cannot be measured in exact number, this method will fail. Another restriction is that this method cannot assign the subjective weights for those criteria. Conversely, the weights are determined by optimization as shown in the above process.

Nolloju (2001) applies the AHP to model a specific class of decentralized decision problems, where many decision makers take individual subjective decisions using locally available information. Group preference aggregation is not applicable to these problems. To deal with these problems, Nolloju (2001) divides the decision makers to several subgroups before aggregates the preference of the decision makers. The approach is mainly used in the problems with many a group of decision makers.

Utility theory is also a popular method used for decision problems (Thurston and Carnahan, 1992; Guyot and Nikolaidis, 1997; Otto and Antonsson, 1991, 1993). Compared to the AHP method, utility theory has stronger axiom basis. However, as Otto and Antonsson (1993) has pointed out, utility theory does not have a property of "annihilation". The term of "annihilation" means that if an alternative of a multi-objective decision problem fails to satisfy any individual goal, the alternative will fail. For example, in an engineering design, the stress limit has to be obeyed for a structure. If this limit is reached, in utility theory, the overall evaluation can be a number greater than zero. However, it is impossible, since the structure will even not work when exceeding stress limit.

To deal with a multiple attribute decision problem, a utility theory based method first determines the single utility functions for each attribute associated with each objective function or constraint. Then the overall utility function for a multiplicative utility function could be determined by the following equation (Keeney and Raiffa, 1976; Guyot and Nikolaidis, 1997),

$$U(\underline{y}) = \frac{1}{\mathrm{k}}\{[\prod_{p=1}^{k+m}(Kk_pU_p(y_p)+1)]-1\}$$

where $y_p$ is the performance of the p-th attribute, and $U_p(y_p)$ is the single utility function of $y_p$, $k_p$ is a constant used to make trade off among the attributes. The value of K is determined by setting $U_p(y_p)$, $k_p$, and $U(\underline{y})$ equal to 1.

In addition to the AHP method and utility theory, fuzzy set theory also can be used in the decision problems (Rao, 1987; Maglaras et al., 1997; Karsak and Tolga, 2001; Lai and Li, 1999; Guyot and Nikolaidis, 1997). Rao (1987) presents a method to solve a fuzzy multi-objective optimization problem using an ordinary single-objective programming technique. First, several single-objective optimization problems can be solved. Then the membership function of the fuzzy objective function may be determined by identifying the minimum and maximum possible values of the objective function and making an assumption that the membership function will be linear. The last step is to solve the question using ordinary optimization method with one more variable than the previous problem.

Karsak and Tolga (2001) propose a multi-criteria decision making procedure to select the most suitable alternative from a set of alternatives. They use a committee, which consists of several members, to evaluate the alternatives. Both the weights and the ratings are fuzzy members. Triangular membership functions are used throughout the analysis. The fuzzy suitability index values are used to rank the alternatives. However, the basic algorithm is still aggregation over the weights and ratings.

Buckley et al. (2001) present a method to find the fuzzy weights in fuzzy hierarchy analysis, by directly fuzzifying the original AHP method used by Saaty (1980). Instead of using direct approach, which is considered too computationally complicated, Buckley et al. (2001) use an equivalent method, Evolutionary Algorithm (EA), to search unknown fuzzy weights.

When constructing the pairwise comparison matrix, the DM is allowed to use fuzzy ratios in place of exact ratios.

Denote $\overline{A} = (\overline{a_{ij}})$ as the pairwise comparison matrix, which is a fuzzy positive, reciprocal matrix. Set $A = (a_{ij})$ as a crisp matrix, which is a subset of the fuzzy matrix set.

From the work of Frobenius (1912), the eigenvector corresponding to the maximum eigenvalue of $A$ is $w$, or

$$w = \lim_{k\to\infty}\left(\frac{A^k e}{e^T A^k e}\right)/c,$$

where e is a n-dimensional vector of all ones, i.e. $e = (1,1,\ldots,1)^T$ , and c is a constant. The obtained eigenvector can be normalized as follows,

$$w' = w/\left(\sum_{i=1}^{n} w_i\right).$$

Since computing the lower bound and upper bound of the fuzzy weights is a complicated non-linear optimization problem, Buckley et al. (2001) recommend the EA to solve the problem.

Two special case of n = 3 and n = 4 are used to compare the EA and direct approach. The results indicate that two methods fit very well (Buckley et al., 2001).

In multi-attribute decision problems, either using the AHP method, or using utility theory and fuzzy set theory, it is important to select a method to determine the overall preference based on single preference for each criterion. Several methods to build overall preference ratings for a designer exist (Otto and Antonsson, 1991, 1993). Generally, max-min approach and product approach are widely used (Otto and Antonsson, 1991, 1993; Yager, 1978).

- Max-min

$$D = \min(A_1, A_2, A_3, \ldots A_p)$$

- Product

$$D = A_1 \cdot A_2 \cdot A_3 \cdot \ldots \cdot A_p$$

Where, $A_i$ is the single evaluation for the ith attribute

D is the overall evaluation

To take the unequal importance into account, each attribute is associated with a non-negative number, which indicates its importance in the decision. Two types of operation can be modified as follows (Yager, 1978),

- Max-min

$$D = \min(A_1^{\alpha_1}, A_2^{\alpha_2}, A_3^{\alpha_3} \cdots, A_p^{\alpha_p})$$

- Product

$$D = A_1^{\alpha_1} \cdot A_2^{\alpha_2} \cdot A_3^{\alpha_3} \cdots A_p^{\alpha_p}$$

The determination of weights can be accomplished by using the AHP method. However, Yager (1978) does not normalize the maximum vector associated with the maximum eigenvalue as Saaty (1980). Instead, Yager (1978) uses the obtained vector directly as the exponents of the objectives.

Guyot and Nikolaidis (1997) present three methods, the conservative method, aggressive method, and moderate method, to combine the membership functions of each objective evaluation into one single overall evaluation.

The conservative method combines membership functions by using the max-min approach. This method is based on the assumption that the overall performance of a system is determined by its poorest attribute.

Allowing higher performance attributes to compensate lower performance attributes, the aggressive method trades off the attributes.

The moderate method is a kind of compromise between the above two methods, since it uses the weighted average of the above two methods.

Those three methods display different results (Guyot and Nikolaidis, 1997). Comparison of three fuzzy set based methods illustrates that the results of the moderate method are a compromise between the results of conservative method and the ones of the aggressive method. Generally, the conservative method tries to equalize the values for all membership functions, since the minimum of the values is the final objective value.

## 3. Methodology

To solve our multi-attribute decision problem, three methods are used, the AHP method, utility theory, and fuzzy set theory respectively.

### 3.1 Modeling using the AHP method

A real world decision model, viewed as a system, may be analyzed by studying its hierarchy, which is an abstraction of the structure of such a system. Hierarchy displays the functional interaction of the components of the system and their impact on the rest of the system. To build a hierarchy structure, the system must be decomposed into disjoint levels, with the elements of one level influencing the elements of only one other level, and being influenced by the elements of only one other level. In this structure, the impact of a level on an adjacent upper level comes from the composition of the relative contributions (priorities) of the elements in that level with respect to each element of the adjacent level (Saaty, 1980). After building a hierarchy, the priorities in hierarchy may be defined. Suppose there are only two levels. Denote $a_{ij}$ as the result of comparing the i-th element with the j-th element, where the results are decided by their relative importance, weight, and brightness etc, according to selected criterion. A pair comparison matrix can be obtained as follows,

$$A = (a_{ij}),\ i,\ j = 1,\ 2,\ \ldots\ n$$

The priority vector will be determined by the normalized principal eigenvector. If there are more than two levels, the various vectors can be combined into priority matrices. They will yield one final vector for the bottom level.

Three levels are obvious in the impact of NIS legislation on the Great Lakes and St. Lawrence Seaway problem. The top level is the ultimate goal of the decision maker. Six elements, namely shipping cost, air pollution, transportation safety, noise pollution, NIS effect, and fuel efficiency, construct the second level. Results from alternative decisions will be the bottom level. The ultimate level and the second level can be linked by a priority vector. Another matrix will link the different alternatives with the second level elements. The final priority may be determined on the product of the priority vector of the first and second level, and the matrix of the second and the third level.

Moreover, the fuzzy set theory may be used to evaluate the comparison matrix, instead of interviewing the decision maker to determine the comparison matrix. First the fuzzy membership functions of the decision maker are constructed. The comparison results are then obtained from the ratio of the fuzzy membership values.

### 3.2 Modeling using utility theory

a. Single attribute utility function

The utility function expresses the preference of the decision maker. There are a lot of techniques to assess the utility function. One of the most popular methods is the probability comparison method.

First, the range of the evaluation values is determined. The utility function value for the best and worst alternative is assigned as follows:

$$u(e_b) = 1,\ \ \mathrm{u}(\mathrm{e}_\mathrm{w}) = 0$$

where $e_b$ is the best alternative,

$e_w$ is the worst alternative.

Then, the decision maker is asked to make selection between a certain alternative and a lottery: $[e_b,\ \mathrm{p}_\mathrm{j},\ \mathrm{e}_\mathrm{w}] \sim e_j$ . The probability $\mathrm{p}_\mathrm{j}$ is the utility function value of the certain alternative.

Finally, the utility function can be determined over the whole range from the worst to best alternative.

To simplify the process in this special illustration problem, a given utility function is used here:

$$u(e_i) = \frac{e^{\rho e_i} - e^{\rho e_w}}{e^{\rho e_b} - e^{\rho e_w}}$$

An additional assessment should be made at the point $(e_b\text{-}\mathrm{e}_\mathrm{w})/2$ . By substitution, the parameter $\rho$ can be determined.

b. Mutual utility independence

Mutual utility independence can reduce the multidimensional utility function to a multiplicative or additive utility function, which may make the decision making problem easier to solve. Keeney and Raiffa (1976) prove that the mutual utility independence can be assessed as follows:

First, the decision maker may select one attribute T1, and build pairs with all of the other attributes. Each of the pairs and its complement will be checked to see if they are preferentially independent. Second, the decision maker must check if the selected attribute T1 is utility independent of its complement. If both checks prove independent, it can be concluded that all attributes are mutually utility independent.

Applying the above method to our problem results in mutually utility independence. This is reasonable for such decision making problem, since these attributes are felt independent to the other attributes. For example, there are two alternatives A and B. Alternative A is preferred to alternative B. When the level of air pollution, fuel efficiency, shipping costs, NIS control, and noise pollution for both alternatives A and B has been shifted from a level to another level, with the level of transportation fixed, the preference between two alternatives will not be changed. It is also true to fix the level of any other five attributes instead of to fix the level of transportation safety.

c. Scaling constants

Scaling constants are used to combine the single attribute utility functions to produce an overall utility function.

First, the scaling constants for all attributes are ranked in descending order. This can be easily accomplished by asking the decision maker a series of questions. An alternative with outcome [w, ... w ] is given, where w is the worst value. Every time, the decision maker is asked to select one to change it from the worst to best. The attribute with the higher scaling constant will be selected earlier. Thus the order of the scaling constants can be determined.

Second, the numerical value can be found by asking the decision maker for the probability $p_j$ such that the two lotteries below are indifferent:

$$[\textit{all at} \text{ best level}, \ p_j, \text{ all at worst level}]$$
$$\sim [\textit{the } \text{j - th attribute at best level,}$$
$$\text{others at worst level}]$$

The left lottery and the right should have the equal expected utility function value. Therefore,

$$u[w, \ldots \mathrm{b}_j, \mathrm{w}] = p_j * u(\textit{all} \text{ at best})$$
$$+ (1 - \mathrm{p}_j) * u(\text{all at worst}) = \mathrm{p}_j$$

The scaling constant $k_j$ is equal to the left part of the equality, thus $k_j = p_j$.

d. Multiplicative or additive model

If the sum of the scaling constants is equal to 1.0, then the additive model can be used here. However, the sum is generally not equal to 1.0, then the multiplicative model should be used.

In the multiplicative case, an additional constant k has to be calculated. It can be determined by using an iterative method. The formula for solving the constant k is the following:

$$1 + k = 1 + \prod_{i=1}^{m} (1 + kk_i)$$

where m is the number of the attributes.

e. Multiple attribute utility function

The multiplicative utility function can be expressed as the following:

$$1 + k\, u(e_1, \ldots e_m) = \prod_{i=1}^{m} (1 + kk_i u_i(e_i))$$

where $u_i$ is the single attribute utility function.

For additive utility function,

$$u(e_1, \ldots e_m) = \sum_{i=1}^{m} k_i u_i(e_i)$$

f. Evaluation

The evaluation can be made in terms of the multiplicative utility function. Given the final overall utility values, the alternatives can be ranked.

### 3.3 Modeling using fuzzy set theory

A procedure using fuzzy set theory to construct a model for the multi-criteria decision problem is presented as follows:

First, the membership function for each attribute is constructed.

Second, the evaluation of alternatives for each attribute is accomplished. This step produces the performance of alternatives based on the six attributes.

Third, the fuzzy evaluation values of every alternative for each attribute are calculated.

Fourth, the weights of attributes are calculated by using the AHP method.

Fifth, the max-min approach or the product approach used by Yager (1978) is used to determine the overall evaluation.

Last, the alternatives are ranked according to their final evaluation values, and the one with the highest such value is selected.

## 4. Numerical example

A real world example follows. Suppose there are three possible NIS control legislative alternatives. Alternative one (A1) is raising the requirement to a high level, which will lead to a high marine freight rate increase. Alternative two (A2) is raising the requirement to a higher level than A1, which will lead to a very high marine freight rate increase. Alternative three (A3) is raising the requirement to a lower level than A1, which will lead to a small marine freight rate increase. These possible marine freight rate increases may force cargo owners to change from the marine to another transportation marine mode. Through calculation, the cargo owners may decide to transport a certain amount of cargo by rail or trucks instead of ships. Since we cannot get the decisions of cargo owners on the distribution of their cargo among the three modes at this moment, we continue using some assumptions. However, the cargo distribution might be determined by using a single attribute decision problem, where the transportation costs for the owners is the single attribute. Let us suppose three possible cargo volumes corresponding to the three above freight rate increases.

One scenario is used: a certain amount of potash from Thunder Bay, Ontario to Toledo, Ohio. Suppose we have obtained the change of amount as 480,000 net tons, 360,000 net tons, and 180,000 net tons for the three legislative alternatives.

The six attributes will be analyzed in the following:

- Transportation safety

According to the transportation safety data (U.S. Department of Commerce, 1999; U.S. Department of Transportation, 2000), the fatal and injury rate for each transportation mode can be shown in the following tables 1 and 2.

- Transportation pollution

According to the air emissions data (U.S. Department of Commerce, 1999; U.S. Environment Protection Agency, 1997, 1998, 2000), the air emissions rate for each transportation mode can be shown in the tables 3 and 4.

- Fuel efficiency

Fuel efficiency data will be calculated from the standard fuel efficiency data (Thorp, 1993). The fuel efficiency data used in this model will be found in the tables 5 and 6.

- Shipping costs

An assumed freight rate (Table 7~8) based on 1993 transportation statistics (U.S. Department of Transportation, 1998) is used here.

- NIS control

The NIS control efficiencies relate to the legislative alternatives directly. Since the standards are not available yet, we have to assume data. The standard is assumed to be that the biological efficiency or other equivalent test result will not exceed some value (say 10%). A reasonable assumption is to view the total ballast water discharge as a control variable. This variable timed by the standard leads to the expected NIS output.

Total potash vessel shipments from Thunder Bay were 1,279,907 net tons in 1990. For a 20,000 deadweight bulk carrier, there are 64 shipments in a year. Ballast water discharges in this scenario are supposed to be 5000 tons each trip, the total ballast water discharges are 320,000 (64x5000) net tons. Assume that the total weight of particles per ton ballast water is 0.005 ton. Therefore total discharges for three alternatives can be obtained (Table 9~10).

- Noise pollution

It is difficult to make a good estimation of the noise pollution of each alternative transportation mode. A reasonable assumption is to take the estimated number of people exposed to the noise into account. That number can be determined by using the following method:

For marine mode, we can calculate the number of calls on ports made by ships. From the number and the population in the ports, we can get the total number of people exposed to noise in this scenario by multiplying the number of calls by the population in the ports. Dividing the obtained results by the total ton-miles results in the rate of noise exposure for marine mode.

For rail and truck mode, the number of trips can be calculated. The total population along the route may be obtained. Thus, we can multiply the trips by the above population. Dividing the obtained results by the total ton-miles results in the rate of noise exposure for truck and rail modes (Table 11~12).

In the following, the decision making problem will be solved by using three methods, the AHP method, utility theory, and fuzzy set theory respectively.

Table 1: Fatality and Injury Rates for Three Transportation Modes
(per million ton-miles)

| Transportation modes | Fatality rates | Injury rates |
|---|---|---|
| Truck | 0.041 | 3.27 |
| Marine | 0.000176 | 0.000416 |
| Rail | 0.001 | 0.012 |

Table 2: Expected Annual Fatality and Injury Rates for the Three Alternatives
(Unit: persons per year)

| Transportation mode | | A1 | A2 | A3 |
|---|---|---|---|---|
| Changes of | Marine fatalities | -0.04169 | -0.05559 | -0.02085 |
| | Rail fatalities | 0.38124 | 0.50832 | 0.19062 |
| | Truck fatalities | — | — | — |
| Total changes of fatalities | | 0.33955 | 0.45273 | 0.16977 |
| Changes of | Marine fatalities | -0.9854 | -0.13139 | -0.04927 |
| | Rail fatalities | 4.57488 | 6.09984 | 2.28744 |
| | Truck fatalities | — | — | — |
| Total changes of injuries | | 4.47634 | 5.96845 | 2.23817 |

Table 3: Air Emission Rates of the Three Transportation Modes
(Unit: short tons per million ton-miles)

| Transportation modes | Carbon Monoxide | Nitrogen Oxide | Volatile Organic Compounds | Sulfur Dioxide | Particulate Matter (PM-10) |
|---|---|---|---|---|---|
| Truck | 1.43 | 1.84 | 0.22 | 0.082 | 0.16 |
| Marine | 0.17 | 0.57 | 0.11 | 0.94 | 0.069 |
| Rail | 0.11 | 0.93 | 0.049 | 0.11 | 0.026 |

Table 4: Changes of Emissions for the Three Alternatives
(Unit: short tons)

| Alternatives | A1 | A2 | A3 |
|---|---|---|---|
| Carbon Monoxide | 11.1 | 14.9 | 5.6 |
| Nitrogen oxide | 219.5 | 292.7 | 109.8 |
| VOC | -7.4 | -9.8 | -3.7 |
| Sulfur Dioxide | -180.7 | -241.0 | -90.4 |
| PM-10 | -6.4 | -8.6 | -3.2 |

Table 5: Fuel Efficiency of the Three Transportation Modes
(Unit: miles per gallon)

| Mode | Marine | Rail | Truck |
|---|---|---|---|
| Fuel Efficiency | 0.0283 | 0.125 | 5.0 |

Table 6: Fuel Consumption for the Three Alternatives
(Unit: gallons)

| Alternatives | A1 | A2 | A3 |
|---|---|---|---|
| Marine | -837,031.8 | -1,116,042.0 | -418,515.9 |
| Rail | 1,219,968.0 | 1,626,624.0 | 609,984.0 |
| Truck | — | — | — |
| Total Fuel Consumption | 382,936.2 | 510,581.6 | 191,468.1 |

Table 7: Assumed Freight Rates of the Three Transportation Modes

| Mode | Marine | Rail | Truck |
|---|---|---|---|
| Total freight bill ($ billion ) | 22 | 34 | 331 |
| Total cargo weight (billion tons) | 2.1 | 1.6 | 6.5 |
| Ton-miles (billion) | 815 | 1200 | 908 |
| Freight Rate ($ per ton-mile) | 0.0270(1) | 0.0283 | 0.365 |

(1) The freight rates for marine mode related to the three legislative options are $0.048, $0.051, and $0.046.

Table 8: Change of Shipping Costs for the Three Alternatives
(Unit: $M)

| Alternatives | A1 | A2 | A3 |
|---|---|---|---|
| Marine costs | 11.37 | 16.11 | 5.45 |
| Rail costs | 10.67 | 14.23 | 5.34 |
| Truck costs | — | — | — |
| Total changes of shipping costs | -0.70 | -1.87 | -0.11 |

Table 9: Total Ballast Water Discharges in the Scenario
(Unit: million tons)

| Alternative | A1 | A2 | A3 |
|---|---|---|---|
| Total Ballast water discharges | 0.23 | 0.20 | 0.275 |

Table 10: NIS Control Efficiencies for the Three Alternatives
(Unit: tons)

| Alternatives | A1 | A2 | A3 |
|---|---|---|---|
| Standard | 10% | 5% | 12% |
| Total ballast water discharge | 230,000 | 200,000 | 275,000 |
| Total particles | 115 | 50 | 165 |

Table 11: Expected Number of People Exposed to Noise in the Scenario
(Unit: million persons per ton-mile)

| | Marine | Rail | Truck |
|---|---|---|---|
| Noise rate | 0.01 | 0.1 | 0.5 |

Table 12: Changes of Expected Number of People Suffering from Noise in the Scenario
(Unit: million persons)

| | A1 | A2 | A3 |
|---|---|---|---|
| Marine | 2.368 | 3.158 | 0.142 |
| Rail | 38.124 | 50.832 | 19.062 |
| Truck | — | — | — |
| Changes of the number of people | 35.8 | 47.7 | 18.9 |

### 4.1 Solution using AHP

The above data for the four alternatives will be presented to the decision maker (DM), who will feed back the DM's preferences over the six attributes. The following matrix represents the DM's preferences of the six attributes.

$$A = \begin{bmatrix} 1 & 1 & 1 & 2 & 1/2 & 1 \\ 1 & 1 & 1 & 2 & 1/2 & 1 \\ 1 & 1 & 1 & 2 & 1/2 & 1 \\ 1/2 & 1/2 & 1/2 & 1 & 1/4 & 1/2 \\ 2 & 2 & 2 & 4 & 1 & 2 \\ 1 & 1 & 1 & 2 & 1/2 & 1 \end{bmatrix}$$

The following six matrices represent the DM's preferences over the four alternatives of each attribute.

For attribute one, transportation safety, we have the following evaluation matrices:

Without fuzzy concept:

$$B1 = \begin{bmatrix} 1.0 & 1.5 & 0.5 \\ 1/1.5 & 1.0 & 0.5 \\ 2.0 & 2.0 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (20, 10, 5, 1, 0, -1, -5, -10, -20).

$$B1 = \begin{bmatrix} 1.0 & 1.24 & 0.74 \\ 0.80 & 1.0 & 0.60 \\ 1.35 & 1.67 & 1.0 \end{bmatrix}$$

For attribute two, air pollution, we have the following evaluation matrices:

Without fuzzy concept:

$$B2 = \begin{bmatrix} 1.0 & 1.0 & 0.8 \\ 1.0 & 1.0 & 0.8 \\ 1/0.8 & 1/0.8 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (500, 100, 50, 20, 0, -20, -50, -100, -500).

$$B2 = \begin{bmatrix} 1.0 & 1.13 & 0.85 \\ 0.88 & 1.0 & 0.75 \\ 1.18 & 1.34 & 1.0 \end{bmatrix}$$

For attribute three, fuel consumption, we have the following evaluation matrices:

Without fuzzy concept:

$$B3 = \begin{bmatrix} 1.0 & 1.5 & 0.5 \\ 1/1.5 & 1.0 & 0.5 \\ 2.0 & 2.0 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (5E5, 2E5, 1E5, 1E4, 0, -1E4, -1E5, -2E5, -5E5).

$$B3 = \begin{bmatrix} 1.0 & 1.39 & 0.67 \\ 0.72 & 1.0 & 0.48 \\ 1.5 & 2.09 & 1 \end{bmatrix}$$

For attribute four, shipping costs, we have the following evaluation matrices:

Without fuzzy concept:

$$B4 = \begin{bmatrix} 1.0 & 0.5 & 1.0 \\ 2.0 & 1.0 & 1.5 \\ 1.0 & 1/1.5 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (10, 5, 2, 1, 0, -1, -2, -5, -10).

$$B4 = \begin{bmatrix} 1.0 & 0.83 & 1.11 \\ 1.21 & 1.0 & 1.35 \\ 0.90 & 0.74 & 1.0 \end{bmatrix}$$

For attribute five, the NIS control, we have the following evaluation matrices:

Without fuzzy concept:

$$B5 = \begin{bmatrix} 1.0 & 1.0 & 1.2 \\ 1.0 & 1.0 & 1.2 \\ 1/1.2 & 1/1.2 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (9E3, 6E3, 4E3, 1E3, 0, -1E3, -4E3, -6E3, -9E3).

$$B5 = \begin{bmatrix} 1.0 & 0.99 & 1.20 \\ 1.01 & 1.0 & 1.21 \\ 0.83 & 0.83 & 1.0 \end{bmatrix}$$

For attribute six, noise pollution, we have the following evaluation matrices:

Without fuzzy concept:

$$B6 = \begin{bmatrix} 1.0 & 1.2 & 0.8 \\ 1/1.2 & 1.0 & 0.6 \\ 1/0.8 & 1/0.6 & 1.0 \end{bmatrix}$$

With fuzzy concept:

The fuzzy membership function uses the triangular fuzzy function type, nine grades are used for the fuzzy assessment. The related nine peak points are (100, 60, 40, 20, 0, -20, -40, -60, -100).

$$B6 = \begin{bmatrix} 1.0 & 1.23 & 0.78 \\ 0.81 & 1.0 & 0.64 \\ 1.28 & 1.57 & 1.0 \end{bmatrix}$$

The solutions of these six matrices are listed below:

Table 13: Vector of Six Attribute Evaluation Matrices
(Without fuzzy concept)

| | Safety | Air Pollution | Fuel Consumption | Costs | NIS control | Noise |
|---|---|---|---|---|---|---|
| A1 | 0.28 | 0.31 | 0.28 | 0.26 | 0.35 | 0.32 |
| A2 | 0.22 | 0.31 | 0.21 | 0.46 | 0.35 | 0.26 |
| A3 | 0.50 | 0.38 | 0.50 | 0.28 | 0.29 | 0.42 |

Table 14: Vector of Six Attribute Evaluation Matrices
(With fuzzy concept)

| | Safety | Air Pollution | Fuel Consumption | Costs | NIS control | Noise |
|---|---|---|---|---|---|---|
| A1 | 0.32 | 0.33 | 0.31 | 0.32 | 0.35 | 0.32 |
| A2 | 0.26 | 0.29 | 0.22 | 0.39 | 0.35 | 0.26 |
| A3 | 0.43 | 0.39 | 0.47 | 0.29 | 0.29 | 0.41 |

The maximum eigenvalue and the related eigenvector for the attribute comparison matrix A:

The maximum eigenvalue, $\lambda_{\max} = 6.0$,

The related eigenvector, $v$ = (0.15, 0.15, 0.15, 0.08, 0.31, 0.15).

Therefore, we get the following decision vector,

Without fuzzy concept:

V = (0.31, 0.29, 0.39)

We find that the third alternative with the maximum priority 0.39. This will be the best alternative according to our evaluation.

With fuzzy concept:

V = (0.33, 0.30, 0.37)

We find that the third alternative with the maximum priority 0.37. This will be the best alternative according to our evaluation.

With appropriate fuzzy membership function, we can obtain consistent results by using the AHP method. The use of fuzzy variables in the AHP method makes the eigenvalue calculation for each single attribute matrix meaningless. Since each single attribute matrix is built by directly comparing fuzzy membership function values of alternatives, the eigenvalue result could be obtained directly from the fuzzy membership function values. However, the eigenvalue calculation for the attributes comparison matrix is still needed, since it does not have the same feature as the single attribute matrix. The attributes comparison matrix indeed gives us the weights of each attribute in global evaluation.

## 4.2 Solution of fuzzy set model using the product approach

The evaluation results of the alternatives are the membership function values of each alternative for six attributes. The weights of six attributes will be determined by the AHP method. The normalized weights for the attribute comparison matrix:

$v$ = (0.15, 0.15, 0.15, 0.08, 0.31, 0.15)

Adopting the product approach will lead to the following results,

$$C = C_1^{0.15} \cdot C_2^{0.15} \cdot C_3^{0.15} \cdot C_4^{0.08} \cdot C_5^{0.31} \cdot C_6^{0.15}$$

where $C_i$ , i=1, 2, 3..., 6, is the component of vector

C is the final evaluation value.

Therefore, we get the following decision vector,

V = (0.329, 0.293, 0.366)

Compared to the overall evaluation value got from the AHP method, (0.330, 0.297, 0.373), the results here are very close to them. And the third alternative with the maximum priority 0.366 will be the best alternative according to our evaluation.

### 4.3 Solution of fuzzy set model using the max-min approach

After obtaining the vector of six attribute evaluation matrices, the results can be derived by using the following formula,

$$C = \min(C_1^{0.15}, \cdot C_2^{0.15}, \cdot C_3^{0.15}, \cdot C_4^{0.08}, \cdot C_5^{0.31}, \cdot C_6^{0.15})$$

where $C_i$ , i = 1, 2, 3…, 6, is the component of vector,

C is the final evaluation value.

For three alternatives, the weighted results are

A1: (0.8429 0.8468 0.8389 0.9129 0.7222 0.8429),

A2: (0.8170 0.8305 0.7968 0.9274 0.7222 0.8170), and

A3: (0.8811 0.8683 0.8929 0.9057 0.6813 0.8748).

Therefore, we get the following decision vector,

V = (0.722, 0.722, 0.681)

We find that the first and second alternative have the maximum priority 0.722. However, the second minimum of the first alternative is 0.8389, which is greater than that of the second alternative, 0.7968. Therefore, the first alternative will be the best alternative according to our evaluation.

The results based on the max-min approach are different from the other two approaches. The alternative that maximizes the minima over all attributes is selected. A basic explanation can be given as follows: the max-min approach tries to find the alternative, which has the most "balanced" attribute.

### 4.4 Solution using multi-attribute utility theory

a. Single attribute utility function

The defined utility function in section 3.2.a is used here:

$$u(e_i) = \frac{e^{\rho e_i} - e^{\rho e_w}}{e^{\rho e_b} - e^{\rho e_w}}$$

Six utility functions are determined as follows:

- Transportation safety

  Use expected annual fatality and injury rates to evaluate.

  $\rho = -1/3$

  $e_b = 1.0$ ( person/year)

  $e_w = 11.0$ (person/year)
- Air pollution

  Use expected annual increase of air pollution to evaluate.

  $\rho = -1/4$

  $e_b = 10.0$ (ton/year)

  $e_w = 100$ (ton/year)
- Fuel efficiency

  Use expected annual increase of fuel consumption to evaluate.

  $\rho = -1/4$

  $e_b = 0.0$ (gallon/year)

  $e_w = 800{,}000$ (gallon/year)
- Shipping costs

  Use expected annual increase of shipping costs to evaluate.

  $\rho = -1/7$

  $e_b = -5.5$ (\$M/year)

  $e_w = 6.5$ (\$M/year)
- NIS control

  Use expected annual amount of particles discharged with ballast water to evaluate.

  $\rho = -1/2$

  $e_b = -15000.0$ (ton/year)

  $e_w = 0.0$ (ton/year)
- Noise pollution

  Use expected annual number of people suffering from noise to evaluate.

  $\rho = -1/4$

  $e_b = 5.0$ (million people/year)

  $e_w = 100.0$ (million people/year)

b. Mutual utility independence

The mutually utility independence can be obtained as discussed in section 3.2.b.

c. Scaling constants

The scaling constants for six attributes are (0.15, 0.15, 0.15, 0.08, 0.32, 0.15). They are obtained from the lottery method mentioned in section 3.2.c.

d. Multiplicative or additive model

The sum of the scaling constants is set equal to 1.0. Since we already have the results of three other methods such as AHP, and two different fuzzy set theory approaches, to compare them in a similar environment, we use additive utility function here. However, in the general case, the multiplicative utility function has to be used. By using the above formula, the constant k can be found.

e. Multiple attribute utility function

An additive utility function is used here based on the above result:

$$u(e_1,\ldots e_m) = \sum_{i=1}^{m} k_i u_i(e_i)$$

f. Evaluation

The evaluation can be made in terms of the multiplicative utility function. Given the three alternatives, the overall utility function values can be ranked.

Single utility function values for the six attributes are given as follows:

Table 15: Single Utility Function Values for Six Attributes

| | Transportation safety | Air pollution | Fuel efficiency | Shipping costs | NIS control | Noise pollution |
|---|---|---|---|---|---|---|
| A1 | 0.0680 | 0.0015 | 0.5524 | 0.3943 | 0.4725 | 0.0005 |
| A2 | 0.0068 | 0.0001 | 0.3909 | 0.5070 | 0.4814 | 0.0000 |
| A3 | 0.3527 | 0.1331 | 0.7829 | 0.3451 | 0.2495 | 0.0400 |

Using the additive model, the utility function values for three alternatives are given as (0.2761, 0.2543, 0.3038). Therefore the best alternative is alternative three, based on utility theory.

The sum of these values is not equal to 1.0. In the AHP method, however, the sum of the final decision vector should be 1.0.

g. A multiplicative model

In the above model, the additive model is used to find the best alternative. However, in real life, a multiple objective decision making problem is more generally a multiplicative model rather than an additive model.

When the sum of the scaling constants is not equal to 1.0, a multiplicative model should be used. Instead of using (0.15, 0.15, 0.15, 0.08, 0.32, 0.15) as the scaling constants vector, (0.25, 0.15, 0.15, 0.1, 0.3, 0.1) is used as the scaling constants vector.

Single utility function values for the six attributes are the same as those of the additive model. The constant k can be calculated by using an iterative method. In this example, the constant k is equal to –0.125.

Using the multiplicative model, the utility function values for three alternatives are given as (0.2782, 0.2531, 0.3336). Therefore the best alternative is alternative three, based on utility theory.

There is no apparent difference in applying multiplicative model and additive model, although the time used to solve the multiplicative model is longer than that used to solve the additive model. The results are similar in these two examples.

### 4.5 Comparison of the four approaches

The results from the AHP method, fuzzy set theory and utility theory indicate that the least amount of cargo shifted will be the most favorable alternative for the decision maker.

The AHP approach gives the easiest way to trade off the attributes by calculating the weighted average of the attributes. The interactive approach gives another way to trade off between the attributes. However, the max-min approach does not trade off between the attributes at all. In the max-min approach, the best alternative is one that maximizes the minima over all attributes.

The main problem in using the utility method is that it will be difficult to determine the utility function. We will need many interviews and consistency checks. However, once the utility function is constructed, the evaluation will be quite easy to execute. The AHP method does not have such an advantage, since it needs the decision maker to make pairwise comparisons between the alternatives.

## 5. Conclusions

In this paper, we model the ballast water treatment related modal shift problem and solve it using three different methods, i.e., utility theory, AHP, and fuzzy set theory. The results indicate that such a modal shift should be avoided, since the less the amount of cargo shifted from the marine mode to other modes, the more favorable the situation is.

We also find that the AHP method might yield a result very quickly if the number of alternatives is not huge. If there are too many iterations, or a lot of alternatives, the AHP method might not be appropriate. Utility theory will be useful if there are a lot of iterations in our evaluation process. However, the construction of the utility function and validation of independence are time-consuming. Fuzzy set theory does not have the above disadvantages. However, proper membership functions have to be assumed to execute this method.

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