Eliciting a Mode of Transportation to Improve Product Life Cycle Performance

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The Pennsylvania State University, University Park, Pennsylvania, 16802, USA
pwp5155@psu.edu

Abstract. The purpose of this paper is to describe how to implement the utility theory to a supply chain problem. In this problem, two different modes of freight transportation are compared to improve life cycle performance of a mass product: trucks and trains. First, the problem is described, the criteria and attributes are introduced and the dataset for this problem is defined. Then, a description of the utility theory model is conducted, explaining the choice of the multiplicative model instead of the additive one. After that, the utility functions for each attribute are elicited, and a trade-off analysis is conducted in order to define indifference points and to calculate the scaling factors. Then, the aggregation function is formulated for this problem, the alternatives ranked, and the best mode of transportation elicited.

Keywords: utility theory, transportation, PLC, product life cycle

1 Introduction

The utility theory is applied to a supply chain problem: eliciting a mode of transportation to improve product life cycle performance of a particular kind of product (refrigerators) on a specific environment (European continent). The problem has been drawn according to [1]. However, [1] does not directly take into account how to ship the refrigerators: there is no information about the mode of transportation used. In order to improve this shortcoming, the aim of this paper is to elicit the best alternative to ship refrigerators.

More specifically, two different modes of freight transportation are taken into account for this problem: trucks and trains. The first mode of transportation is represented by three different types of general freight truck, divided by mileage: less than 250 miles (truck type A), between 250 and 500 (truck type B), and over 500 miles (truck type C), according to [2]. Trucks are well known to be flexible, they require little time to be loaded, and they do not need railroad facilities: they can easily go wherever there is an asphalted road. Trucks' drawbacks are pollution emissions and higher cost per ton per mileage.

On the other hand, trains are reasonably flexible, less expensive than trucks and produce much less emissions. The main drawback of trains is the journey time:

given that trains usually may carry a large quantity of goods, loading time is consequently longer compared to trucks. In this analysis, four different trains have been taken into account: Heavy Unit Train, Mixed Freight Train, Intermodal Train, and Double-stack Container Train [2].

2 Criteria and Attributes

In order to rank the alternatives, three criteria have been considered relevant for this problem: flexibility, cost, and emissions. For each criterion, different attributes have been used, as follows:

- Flexibility:
  - Maximum distance that the mean of transportation can cover (max dist.)
  - Maximum load that can be carried (max load)
  - The average speed of the truck or train (avg. speed)
  - The easiness to restore, repair, and replace truck or train (eas. to R/R)
- Environmental Impact:
  - The amount of NO_X gas emitted by the mode of transportation (NO_X)
  - The amount of CO_2 gas emitted by the mode of transportation (CO_2)
  - Environmental Risk: based on the overall environmental impact and footprint (env. risk)
- Average Cost per Ton Mile (avg. cost p t-m)

Some data has been drawn by [2], others (avg. speed, eas. to R/R and env. Risk) have been calculated by using some assumptions and making estimation: for this reason the data in input is affected by some variations, and it introduces a source of uncertainty in the model. For instance, data may slightly vary depending on the driving condition, the maintenance status of the engine, the type of road and several other factors. For this purpose, utility theory has been developed for this problem. The dataset for the problem is reported as follows:

Table 1. Attribute dataset ([2], except for avg speed, easinees to R/R and env. risk)

	Flexibility (max)				Environmental Impact (max)			Cost (min)
	Max Dist. (miles)	Max Load (tons)	Avg. Speed (mph)	Eas. to R/R	NO_X (g/ mile)	CO_2 (g/ mile)	Env. Risk	Avg cost p t-m (cents)
Truck type A	350	7.26	23.68	8.5	2.390	34.88	1	21.17
Truck type B	750	14.77	27.61	10	1.88	94.62	2	8.94
Truck type C	1250	15.61	30.41	8	16.12	134	2.50	7.69
Heavy Unit train	1000	10500	9.62	1	0.257	22	10	1.19
Mixed Train	500	6300	7.81	3.5	0.322	18.60	7.5	1.20
Intermodal Train	1750	3360	24.65	5.5	0.603	17	6	2.68
Double stack	1750	6720	18.42	2	0.400	15.40	7	1.06

3 Utility Function Elicitation

In this section, the utility function elicitation is performed. First, for each attribute, it is necessary to define a function and its parameters. In this way, for each attribute, it is possible to calculate the utility that corresponds to each level of the attributes itself. The utility range goes from zero to one. The utility function gives a value of zero to the worst level of each attribute, and a utility of one to the best level. The largest or the smallest number of each attribute is considered the best or worst case depending on the minimization or maximization of that particular attribute.

3.1 Mathematical Model of the Utility Function

In this section, we first describe the method used to determine the utility function for each attribute. Among the several different types of function that can be used, the exponential function is the most popular. This is due to the fact that it is sufficient to define only one parameter (RT) to describe the curve. In this case study, we use the exponential function, which is reported as follows:

$$U(x) = A - B * EXP\left(-\frac{x}{RT}\right) \tag{1}$$

Where U(x) is the utility of consequence x; RT is the parameter that determines the curvature and it is called risk tolerance (it determines if the DM is risk adverse, risk neutral or risk seeking); EXP is the exponential function; A and B the scaling parameters. These two parameters depend on RT too, as follows:

$$A = \frac{EXP\left(-\frac{Low}{RT}\right)}{\left[EXP\left(-\frac{Low}{RT}\right) - EXP\left(-\frac{High}{RT}\right)\right]} \tag{2}$$

$$B = \frac{1}{\left[EXP\left(-\frac{Low}{RT}\right) - EXP\left(-\frac{High}{RT}\right)\right]} \tag{3}$$

In order to define the RT parameter, three points must be defined. Two points are the end points of the dataset, corresponding to the best and the worst case; the third point is chosen by the decision maker by using the certainty equivalent. This is the amount of payoff (in terms of utility) that the decision maker is willing to receive to be indifferent between that payoff and a given gamble [3]. The certainty equivalent is calculated as follows:

$$CE = -RT * LN\left[\frac{A - EU}{B}\right] \tag{4}$$

Where CE is the certainty equivalent; RT is the risk tolerance parameter (that we want to find); LN is the natural logarithm function; and EU the expected utility.
In order to estimate the correct value of RT for three given points (best case, worst case, and certainty equivalent), it is possible to use the following:

$$A - B * EXP\left(-\frac{CE}{RT}\right) = .5\left[A - B * EXP\left(-\frac{High}{RT}\right)\right] + .5\left[A - B * EXP\left(-\frac{Low}{RT}\right)\right] \quad (5)$$

Equation (5) states that the utility of CE must be equal to the expected utility of the lottery. The value of RT that verifies this equivalence should be used to describe the curve.

3.2 The Utility Function Elicitation for Each Attribute

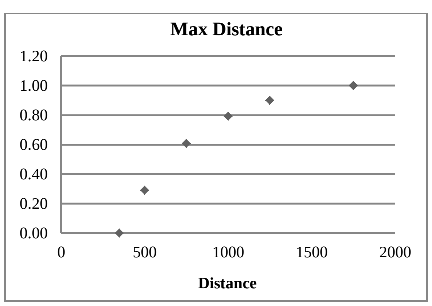
In this section, the utility functions are elicited for each attribute. For any of them, the assessment inputs are chosen; the risk tolerance and the scaling factors are calculated; the function is drawn; and finally the utility for each alternative is reported.

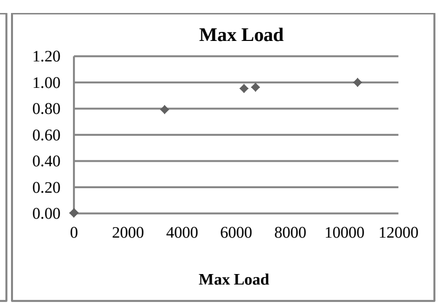
Table 2. Assessment inputs and outputs for the attributes

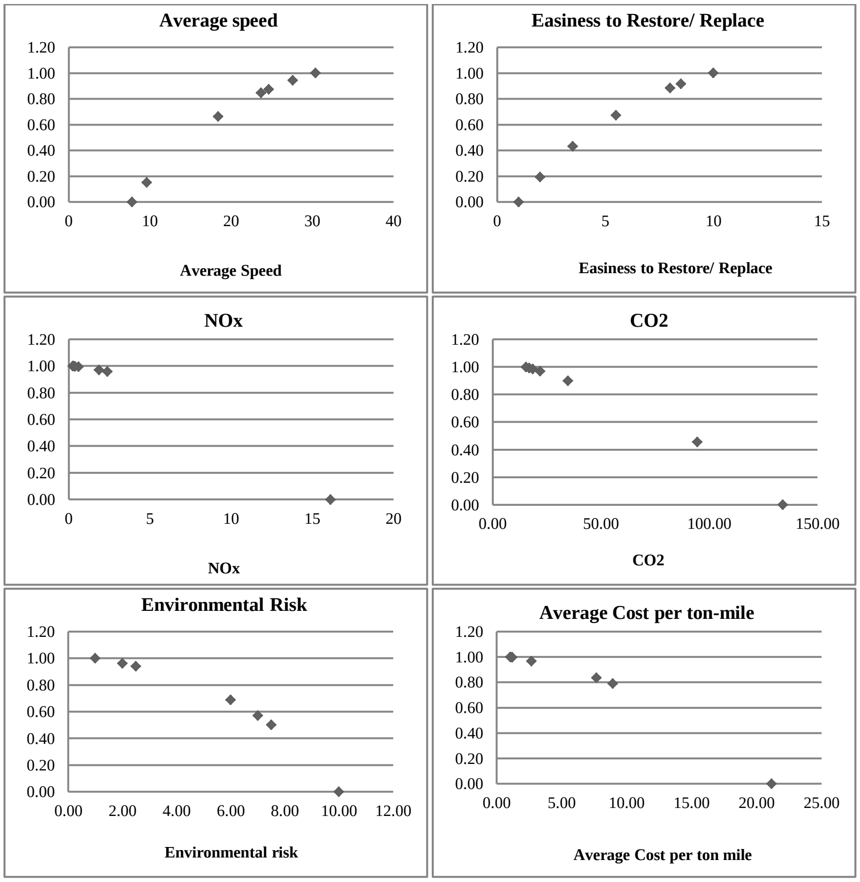
	Max Dist. (miles)	Max Load (tons)	Avg. Speed (mph)	Eas. to R/R	NO_X (g/ mile)	CO_2 (g/ mile)	Env. Risk	Avg. cost p t-m (cents)
Assessment Inputs								
Worse Payoff	350	7.26	7.81	1	16.12	134	10	21.17
Certain Equiv.	650	1500	15	4	12	90	7.5	15
Better Payoff	1750	10500	30.41	10	0.257	15.4	1	1.06
Assessment Outputs								
Risk Tol.	465.03	2181.97	14.11	6.23	-6.89	-109.77	-4.36	-11.64
A (2)	1.052	1.008	1.253	1.309	1.111	1.514	1.146	1.216
B (3)	2.233	1.012	2.178	1.537	0.107	0.447	0.116	0.197

All the functions have been built from a risk adverse prospection. In fig.1, the utility functions for the eight attributes are reported. It is possible to notice the risk aversion in the concavity of the curves, as follows:

Fig. 1. Table 3. Utiliy Functions







4 The Multiplicative Aggregation Method

The choice of the multiplicative method is required whenever the attributes involved are correlated among each other. As soon as there is at least one significant correlation among two variables, a multiplicative model must be used. In our problem, there are some strong correlations (positive or negative) among the attributes, which are reported as follows:

- Average cost per ton-mile is negatively correlated (ρ= -.72) with the maximum load: the higher is the load, the lower is the average cost per ton-mile
- The pollutant gases NO_X and CO_2 are positively correlated (ρ= .85)
- The environmental risk is highly correlated with the maximum load (ρ= .97)

Since there are some correlations among the problem's attributes, the multiplicative model has been implemented. According to [4], the overall utility is given by the following:

$$U(x_1, \dots, x_n) = \frac{1}{K}\left[\prod_{i=1}^{n}(K k_i u_i(x_i) + 1) - 1\right] \quad (6)$$

Where, u_i is the utility of the attribute x_i and it is defined by the utility function, k_i is the scaling factor of the attribute x_i, and it will be defined using a trade-off comparison analysis among the attributes, and K is a non-zero solution to the equation [4]:

$$K + 1 = \prod_{i=1}^{n}(1 + K\, k_i) \quad (7)$$

The utility function have been elicited for each attribute, and the value of $u_i(x_i)$ have been defined (by using values in Table 2). Then, the k_i are defined, throughout a trade-off comparison among the attributes.

5 Scaling Factors Elicitation

In this section, the scaling factors for the multiplicative model are defined (k_i). First, it is necessary to rank the attributes, and then, a value for the scaling factor of the most important criteria is assigned. The other scaling factors are defined by comparing them with an equivalent level of the most important criteria.

5.1 Criteria Ranking

The first step is to define the ranking of the each attribute. The criteria have been ranked as follows:

Table 3. Attributes ranking

Criteria	k_i	Attribute	Rank
Flexibility (maximize)	1	Max Dist. (miles)	2
	2	Max Load (tons)	2
	3	Avg. Speed (mph)	7
	4	Eas. to R/R	3
Environmental Impact (minimize)	5	NO_X (g/ mile)	5
	6	CO_2 (g/ mile)	6
	7	Env. Risk	4
Cost (minimize)	8	Avg cost p t-m (cents)	1

The most important criterion is cost. The maximum distance and the maximum load are both equally important and they occupy the second position of the ranking. The easiness to replace the mean of transport is in the fourth position, followed by environmental risk, and by the two pollutant gases (NO_x and CO_2). The last position belongs to average speed. As specified in the previous sections, the average speed is considered to be so relevant for this problem. Consequently, k_i's are ranked as follows [5]:

$$k_8 > k_1 = k_2 > k_4 > k_7 > k_5 > k_6 > k_3 \tag{8}$$

5.2 Determination of the Indifference Points

The third step is to determine the scaling factors for all of the attributes. One method is determining the indifference points by comparing the best level of any sub-criterion (x_i) to an equivalent trade-off level of the most important criterion (x_8). According to (8), the most important scaling factor is average cost per ton mile, and its value has been assumed equal to the following:

$$k_8 = 0.4 \tag{9}$$

The trade-offs for the other attributes have been assumed equal to the following:

$$(x_1 = 350, x_8 = 4.5) \approx (x_1 = 1750, x_8 = 21.17)$$

$$(x_4 = 1, x_8 = 5.5) \approx (x_4 = 10, x_8 = 21.17)$$

$$(x_7 = 10, x_8 = 8) \approx (x_7 = 1, x_8 = 21.17)$$

$$(x_5 = 16.12, x_8 = 10) \approx (x_5 = 0.257, x_8 = 21.17)$$

$$(x_6 = 134, x_8 = 13) \approx (x_6 = 15.4, x_8 = 21.17)$$

$$(x_3 = 7.81, x_8 = 18) \approx (x_3 = 30, x_8 = 21.17)$$

The trade-offs lead to:

$$k_1 = k_2 = .343, k_4 = .316, k_7 = .265, k_5 = .224, k_6 = .245, k_3 = .116 \tag{10}$$

5.3 K elicitation

In order to calculate the value of K, it is necessary to plug-in the values of the k_i's that have been determined by the trade-off comparison, and substitute them in (7), where K is a non-zero solution of the equation (7). Among all the roots of the equation, the expert choice is to choose the largest one. The highest non-zero K value of the equation is K = -0.90974.

6 Aggregation Utility and Results

In this section, the utility function is finally calculated. Using (6), it is possible to plug in the data we have for each alternative, calculate the overall utility for each alternative, and rank them according to it. The result is the following:

Table 4. Utility and ranking for each alternative

Alternative	Utility	Ranking
Truck type A	0.732657	7
Truck type B	0.866891	5
Truck type C	0.815110	6
Heavy Unit train	0.874521	4
Mixed Train	0.883914	3
Intermodal Train	0.958810	1
Double stack	0.941066	2

The best alternative is the intermodal train, which scores pretty high in the three most important attributes: max distance, max load and average cost. In general, it is possible to notice that the overall utility score of the four trains is slightly higher than the three trucks. This is due to the fact that trains score higher than trucks on “maximum distance”, “average cost”, and “maximum load”. Moreover, trains have a higher score for what concerns the environmental impact’s attributes (e.g. NO_X and CO_2 emissions are lower for trains than for trucks).

7 Conclusions

In this paper all the aspects of utility theory have been covered. First, the problem has been introduced, the attributes have been defined, and the utility functions for each attribute have been elicited. Then, the multiplicative aggregation model introduced, indifference points defined, scaling factors calculated, and the K elicited. Finally, the alternatives have been ranked based on the overall utility: the best alternative is the intermodal train and the worst is the general freight truck type A. In general, trains have a higher score compared to trucks. This is due to the fact that trains have a higher utility in the most important attributes, as average cost, max load, max distance, and gas emissions.

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