Selection of hazardous industrial waste transportation firm using extended VIKOR method under fuzzy environment

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Abstract: Hazardous and toxic industrial wastes may cause or significantly contribute to extensive damage to both humans and the environment when improperly handled. Evaluation of the proper and most appropriate hazardous industrial waste transportation firm is an important problem for hazardous waste generators. In general, many factors affect the appropriate hazardous industrial waste transportation firm selection problem which adheres to uncertain and imprecise data, and usually several people from different functional areas of the company are involved in this process. In this paper, an improved and more effective hazardous industrial waste transportation firm selection model has been developed through integrating VIKOR method with fuzzy set theory. A numerical example is proposed to illustrate an application of the proposed model.

Keywords: Delphi method; fuzzy set; hazardous industrial waste; multicriteria decision making; MCDM; VIKOR method.

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1 Introduction

Wastes can be defined as materials which no longer can be used for the purposes they were intended for originally. In modern societies almost everything (materials, devices, objects, etc.) sooner or later become a waste (Gumus, 2009) and new types of pollutants.

Alloway (1995) classified waste into four types like Agricultural, industrial, municipal and nuclear. Based on its properties, waste can be inert (non-hazardous) or hazardous.

A definition of hazardous waste was established for the first time in the USA at the beginning of the 1980s (Marinkovic et al., 2008). It encompasses all substances that are hazardous to human health and the environment. A waste can be characterised as hazardous if it possesses any one of the following four characteristics: Ignitability, corrosiveness, reactivity or toxicity. Within the broad framework of the United Nations Environmental Programme (UNEP) definition, a waste can be considered to be hazardous if it exhibits one or more of the given attributes (Musee et al., 2006). Flammability refers to wastes capable of creating fires during routine management. This property depends on the flash point of the material. Reactivity is the ability of a material to react both with it and other materials under normal conditions. Toxicity is a measure of the ability of a material to pose substantial hazard to human health or the environment. Organisms are exposed to toxic chemicals through inhalation, ingestion, or skin absorption pathways. Corrosivity refers to the capability of a material to corrode metals owing to the strength of its acidity or alkalinity.

Hazardous wastes, which are usually the waste by products of our industrial processes, present immediate or long-term risks to humans, animals, plants, or the environment (Alumur and Kara, 2007). Hazardous wastes are viewed as wastes that may cause or significantly contribute to extensive damage to both humans and the environment when poorly handled (Musee et al., 2006; Yesilnacar and Cetin, 2005). Hazardous and toxic industrial wastes are wastes which by their nature and quality may be potentially detrimental to human health and/or the environment and which require special management, treatment and disposal (Emek and Kara, 2007). Many types of businesses generate hazardous waste. Some of these businesses are small-scale ones located in communities, such as dry cleaners, auto repair shops, hospitals, exterminators, and photo processing centres, and some hazardous waste generators are larger businesses like chemical manufacturers, electroplating companies, and petroleum refineries. In addition to these industries, there are also hazardous household waste such as batteries, gasoline, antifreeze, oil-based paints and thinners, household cleaning products and pesticides (Alumur and Kara, 2007; Musee et al., 2006; Gumus, 2009).

The planning and design of a regional hazardous waste management system involves selection of transportation-treatment and disposal facilities, allocation of hazardous wastes and waste residues from generator to the treatment and disposal sites, and selection of the transportation routes (Nema and Gupta, 1999). The problem of hazardous waste generation, storage, treatment, transport, recycling, recovery and safe disposal has become an issue of major international concern, particularly for developing countries (Khan and Anjaneyulu, 2003; Yesilnacar and Cetin, 2005).

For many producers of hazardous waste, transport legislation is way down the priority list because someone else handles this process for them. However, there are some important compliance issues to consider. Firstly, there is a duty of care to ensure that those who carry waste on your behalf are licensed to do so and are competent and carry out the process within the law. Secondly, although you may not actually transport your waste, you must make sure that your waste is suitably prepared for transport. Finally, you are still affected by the chemicals (hazard information for packaging and supply) regulations (CHIP) in the way you label and package your waste (Orford, 2007).

The industrial and technological advances of the last two centuries have created a significant hazardous waste management problem in the developed world. The solution to the hazardous waste management problem comes from different perspectives. There are various objectives to managing the problem in a safe and cost-effective manner (Gumus, 2009). For example, for a carrier firm, the best solution would be the one with the least cost, while for the government; the best solution would be the one with the least risk. One should select a compromise solution considering these different objectives (Alumur and Kara, 2007). The chosen transportation firm must have the capacity to operate the legal procedure and acts correctly. Also, it is important to the firm to have the consciousness of quality, service, safety and responsibility. Another factor to be considered is that hazardous waste transportation is a specific task and so burdens the transportation firm additional costs if compared to non-hazardous waste transportation tariff (Ho, 2011).

There is a need for a systematic and logical scientific method or mathematical tool to guide user organisations in taking a proper hazardous industrial waste transportation firm (HIWTF) selection decision. The objective of a HIWTF selection procedure is to identify the HIWTF selection attributes and obtain the most appropriate combination of HIWTF selection attributes in conjunction with the real requirement. Thus, efforts need to be extended to determine attributes that influence HIWTF selection, using a simple logical approach, to eliminate unsuitable HIWTF and selection of a proper HIWTF to strengthen the existing HIWTF selection procedure.

In this paper, the concept of fuzzy sets theory is integrated with Delphi and VIKOR methods to develop a systematic decision process for selecting HIWTF. In this study, extended VIKOR method is applied, which was developed for multi-criteria optimisation for complex systems, to find a compromise priority ranking of alternatives according to the selected criteria for a selection problem. The Delphi method is an iterative process used to collect and distil the judgments of experts using a series of questionnaires interspersed with feedback (Kabir and Sumi, 2013). Therefore, it de-livers qualitative as well as quantitative results and has beneath its explorative, predictive even normative elements (Yalcin et al., 2012). The Delphi technique is an appropriate methodology for identifying the significant factors and issues for the evaluation and selection of HIWTF. The VIKOR method was developed to solve multi-criteria decision making problems with conflicting and non-commensurable (different units) criteria, assuming that compromising is acceptable for conflict resolution, the decision maker wants a solution that is the closest to the ideal, and the alternatives are evaluated according to all established criteria. This method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria, and on proposing compromise solution (one or more) (Opricovic and Tzeng, 2007). The objective of this study was to determine the priority ranking of HIWTFs using VIKOR method under fuzzy environment for the overall improvement of the organisation.

The remainder of this paper is organised as follows. In the next section an overview and the concepts of the Delphi method, VIKOR method and fuzzy sets are given. In the following section, proposed methodology has been described step by step under fuzzy environment. The proposed methodology is applied to evaluate and select the suitable

HIWTF of an automotive battery manufacturing company in Bangladesh in the next section. Finally, the last section presents the conclusion and discusses the limitations and scope for future research.

2 Literature review

There is increasing popularity of selection or modelling of hazardous or infectious waste transportation or disposal firms. Hsu et al. (2008) proposed modified Delphi method and analytic hierarchy process (AHP) for the selection of medical waste disposal firms. Based on the results of interviews with experts in the field, they tried to reduce overhead costs and enhance medical waste management. Karamouz et al. (2007) presented a framework for managing hospital solid wastes considering different criteria which are usually used for evaluating the pollution of hospital solid waste loads. In order to rank the hospitals and determine the share of each hospital in the total hospital solid waste pollution load, analytical hierarchy process was used. Khan and Faisal (2008) introduced a hierarchical network (hiernet) decision structure and apply the analytic network process (ANP) super-matrix approach to select appropriate municipal solid waste disposal methods. ANP measure the relative desirability of disposal alternatives using value judgments as the input of the various stakeholders. Combining multicriteria decision making (MCDM) with consensus analysis model (CAM), Hung et al. (2007) developed a sustainable municipal solid waste management (MSWM) model. In another study, a two step methodology is structured to evaluate hazardous waste transportation firms containing the methods of fuzzy analytic hierarchy process (FAHP) and technique for order preference by similarity to ideal solution (TOPSIS) (Gumus, 2009). Faisal et al. (2011) proposed an analytic framework to provide infectious waste management experts for prioritising factors for selection of contractors managing infectious waste. FAHP has been used to identify the infectious solid waste factors for selecting best contractor. Ho (2011) employed FAHP to set the objective weights of the evaluation criteria and select the optimal infectious medical waste disposal firm through calculation and sorting.

The application of VIKOR method has been increasing. In the literature, Liou et al. (2011) used a modified VIKOR method for improving the domestic airlines service quality and Chang and Hsu (2009) used VIKOR method for prioritising land-use restraint strategies in the Tseng-Wen reservoir watershed. Sayadi et al. (2009) used extension VIKOR method for the solution of the decision making problem with interval numbers. On the other hand some researchers have evaluated VIKOR method under fuzzy environment. For example, Kaya and Kahraman (2010) used an integrated fuzzy VIKOR and AHP methodology for multi-criteria renewable energy planning in Istanbul and also Sanayei et al. (2010) used VIKOR method for a supplier selection problem with fuzzy sets. Chen and Wang (2009) optimised partners' choice in IS/IT outsourcing projects by fuzzy VIKOR. Yücenur and Demirel (2012) used the extended VIKOR method to analyse five Turkish insurance companies for a foreign investor who wants to purchase a local insurance company. Yalcin et al. (2012) used FAHP with TOPSIS and VIKOR for financial performance evaluation of Turkish manufacturing industries.

3 Methodology

3.1 Delphi method

The Delphi method accumulates and analyses the results of anonymous experts that communicate in written, discussion and feedback formats on a particular topic. Anonymous experts share knowledge skills, expertise and opinions until a mutual consensus is achieved (Chang et al., 2008; Hsu et al., 2008). The Delphi method consists of five procedures:

1 select the anonymous experts

2 conduct the first round of a survey

3 conduct the second round of a questionnaire survey

4 conduct the third round of a questionnaire survey

5 integrate expert opinions and to reach a consensus.

Steps 3 and 4 are normally repeated until a consensus is reached on a particular topic (Chang et al., 2008; Gumus, 2009). Results of the literature review and expert interviews can be used to identify synthesise all common views expressed in the survey (Kabir and Hasin, 2012; Kabir and Sumi, 2012). Therefore, this study develops quality evaluation criteria for selection of HIWTFs by conducting interviews with anonymous experts.

3.2 VIKOR method

Opricovic (1998) and Opricovic and Tzeng (2002) developed VIKOR, the Serbian name: VlseKriterijumska Optimizacija I Kompromisno Resenje, means multi-criteria optimisation and compromise solution (Chu et al., 2007). The VIKOR method was developed for multi-criteria optimisation of complex systems (Opricovic and Tzeng, 2004). This method focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria, which can help the decision makers to reach a final decision. Here, the compromise solution is a feasible solution which is the closest to the ideal, and a compromise means an agreement established by mutual concessions (Opricovic and Tzeng, 2007). It introduces the multi-criteria ranking index based on the particular measure of 'closeness' to the 'ideal' solution (Opricovic, 1998).

According to Opricovic and Tzeng (2004) the multi-criteria measure for compromise ranking is developed from the PL_p-metric used as an aggregating function in a compromise programming method (Yu, 1973). The various J alternatives are denoted as $a_1, a_2, \ldots, a_J$. For alternative a_j, the rating of the i^{th} aspect is denoted by f_{ij}, i.e., f_{ij} is the value of i^{th} criterion function for the alternative a_j; n is the number of criteria. Development of the VIKOR method started with the following form of L_p-metric:

$$L_{p,j} = \left\{ \sum_{i=1}^{n} \left[w_i \left(f_i^* - f_{ij} \right) \big/ \left(f_i^* - f_i^- \right) \right]^p \right\}^{\frac{1}{p}}, \quad 1 \le p \le \infty; \quad j = 1, 2, 3, \ldots, J. \tag{1}$$

Within the VIKOR method $L_{1,j}$ [as S_j in equation (15)] and $L_{1,j}$ [as R_j in equation (16)] are used to formulate ranking measure. $L_{1,j}$ is interpreted as 'concordance' and can provide decision makers with information about the maximum group utility' or 'majority'. Similarly, $L_{1,j}$ is interpreted as 'discordance' and provides decision makers with information about the minimum individual regret of the 'opponent' (Sanayei et al., 2010; Sayadi et al., 2009).

3.3 *Fuzzy approach*

In dealing with a decision process, the decision maker is often faced with doubts, problems and uncertainties. In other words natural language to express perception or judgment is always subjective, uncertain or vague (Baek and Prabhu, 2008). To resolve the vagueness, ambiguity and subjectivity of human judgment, fuzzy sets theory (Zadeh, 1965) was introduced to express the linguistic terms in decision making (DM) process. Bellman and Zadeh (1970) developed fuzzy multicriteria decision making (FMCDM) methodology to resolve the lack of precision in assigning importance weights of criteria and the ratings of alternatives regarding evaluation criteria (Mohanty et al., 2010).

A fuzzy set is a set of objects in which there is no clear-cut or predefined boundary between the objects that are or are not members of the set. The key concept behind this definition is that of 'membership': any object may be a member of a set 'to some degree'; and a logical proposition may hold true 'to some degree'. Each element in a set is associated with a value indicating to what degree the element is a member of the set (Singh et al., 2012). This value comes within the range [0, 1], where 0 and 1, respectively, indicate the minimum and maximum degree of membership, while all the intermediate values indicate degrees of 'partial' membership (Wang and Liang, 2009). This approach helps decision makers solve complex decision making problems in a systematic, consistent and productive way and has been widely applied to tackle DM problems with multiple criteria and alternatives (Curry and Lazzari, 2009). In short, fuzzy set theory offers a mathematically precise way of modelling vague preferences for example when it comes to setting weights of performance scores on criteria. Fuzzy set theory was also looked at as a tool for HIWTF selection because of the vagueness of the information related to parameters.

In the following, for the purpose of reference, some important definitions and notations of fuzzy sets theory from Hatami-Marbini et al. (2011), Sanayei et al. (2010) and Zadeh (1975) will be reviewed.

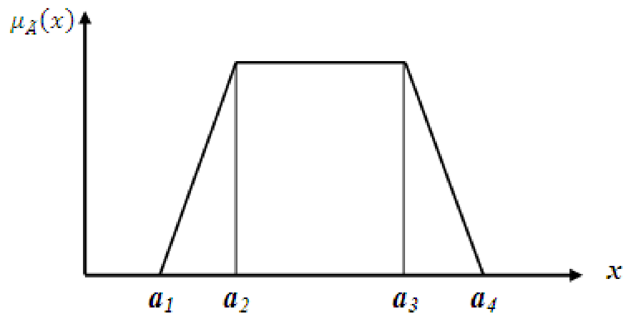
Let X be the universe of discourse, $X = \{x_1, x_2, \ldots, x_n\}$. A fuzzy set $\tilde{A}$ of X is a set of order pairs, $\{(x_1 f_{\tilde{A}}(x_1)), (x_2 f_{\tilde{A}}(x_2)), \ldots, (x_n f_{\tilde{A}}(x_n))\}$, $f_{\tilde{A}}\ X \rightarrow [0,1]$ is the membership function of $\tilde{A}$, and $f_{\tilde{A}}(x_i)$ stands for the membership degree of x_i in $\tilde{A}$. The value $f_{\tilde{A}}$ is closer to 0, the degree is low. The value $f_{\tilde{A}}$ is closer to 1, the degree is high.

A fuzzy set $\tilde{A}$ of the universe of discourse X is convex if and only if for all x_1, x_2 in X, $f_{\tilde{A}}(\lambda x_1 + (1-\lambda)x_2) \geq \min[f_{\tilde{A}}(x_1), f_{\tilde{A}}(x_2)]$, where $\lambda \varepsilon [0, 1]$, $x_1, x_2 \varepsilon X$.

The height of a fuzzy set is the largest membership grade attained by any element in that set. A fuzzy set $\tilde{A}$ in the universe of discourse X is called normalised when the height of $\tilde{A}$ is equal to 1. A fuzzy number is a fuzzy subset in the universe of discourse X that is both convex and normal. There are different types of fuzzy membership function. This paper adopts the type of a trapezoidal fuzzy number. A positive trapezoidal fuzzy number $(\text{PTFN})_c$ can be defined as (a_1, a_2, a_3, a_4), shown in Figure 1. The membership function $\mu_{\tilde{A}}(x)$ is defined as:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a_1, \\ \dfrac{x - a_1}{a_2 - a_1} & a_1 \le x \le a_2, \\ 1, & a_2 \le x \le a_3, \\ \dfrac{x - a_4}{a_3 - a_4} & a_3 \le x \le a_4, \\ 0, & x > a_4, \end{cases} \tag{2}$$

Figure 1 Trapezoidal fuzzy number $\tilde{A}$



A non-fuzzy number r can be expressed as (r, r, r, r). By the extension principle, the fuzzy sum ⊕ and fuzzy subtraction Θ of any two trapezoidal fuzzy numbers are also trapezoidal fuzzy numbers; but the multiplication ⊗ of any two trapezoidal fuzzy numbers is only an approximate trapezoidal fuzzy number. Given any two positive trapezoidal fuzzy numbers, $\tilde{a} = (a_1, a_2, a_3, a_4)$, $\tilde{b} = (b_1, b_2, b_3, b_4)$ and a positive real number r, some main operations of fuzzy numbers $\tilde{A}$ and $\tilde{B}$ can be expressed as follows:

$$\tilde{A} \oplus \tilde{B} = [a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4], \tag{3}$$

$$\tilde{A}\ \Theta\ \tilde{B} = [a_1 - b_1, a_2 - b_2, a_3 - b_3, a_4 - b_4], \tag{4}$$

$$\tilde{A} \otimes \tilde{B} = [a_1 b_1, a_2 b_2, a_3 b_3, a_4 b_4], \tag{5}$$

$$\tilde{A} \otimes r = [a_1 r, a_2 r, a_3 r, a_4 r], \tag{6}$$

The operations of (max) and (min) are defined as follow:

$$\tilde{A}\ (\mathrm{V})\ \tilde{B} = (a_1\ \mathrm{V}\ b_1, a_2\ \mathrm{V}\ b_2, a_3\ \mathrm{V}\ b_3), \tag{7}$$

$$\tilde{A}\ (\Lambda)\ \tilde{B} = \left(a_1\ \Lambda\ b_1, a_2\ \Lambda\ b_2, a_3\ \Lambda\ b_3\right), \tag{8}$$

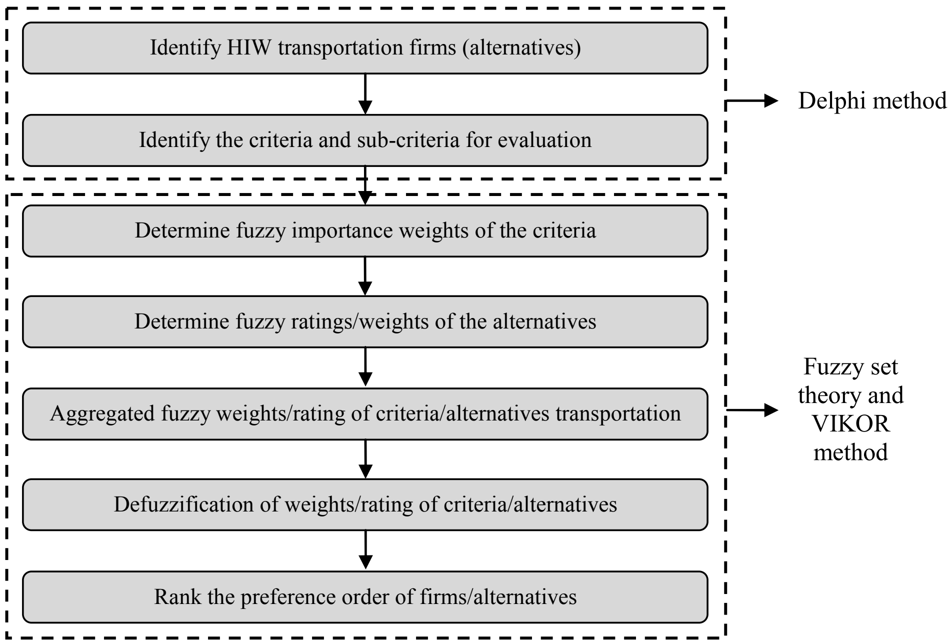
Also the crisp value of the fuzzy number $\tilde{A}$ based on centre of area (COA) method can be expressed by following relation:

$$\begin{aligned} defuzz\left(\tilde{A}\right) &= \frac{\int x.\mu(x)dx}{\int \mu(x)dx} \\ &= \frac{\int_{a_1}^{a_2}\left(\frac{x-a_1}{a_2-a_1}\right).xdx + \int_{a_2}^{a_3} xdx + \int_{a_3}^{a_4}\left(\frac{a_4-x}{a_4-a_3}\right).xdx}{\int_{a_1}^{a_2}\left(\frac{x-a_1}{a_2-a_1}\right)dx + \int_{a_2}^{a_3} dx + \int_{a_3}^{a_4}\left(\frac{a_4-x}{a_4-a_3}\right)dx} \\ &= \frac{-a_1a_2 + a_3a_4 + \frac{1}{3}\left(a_4-a_3\right)^2 - \frac{1}{3}\left(a_2-a_1\right)^2}{-a_1-a_2+a_3+a_4} \end{aligned} \tag{9}$$

4 Proposed methodology for HIWTF selection

A systematic approach to extend the VIKOR is proposed to solve the HIWTF selection problem under a fuzzy environment in this section. This methodology steps or levels can be seen in Figure 2. The steps of the methodology are detailed theoretically in following subsections.

Figure 2 The levels of hazardous industrial waste transportation firm selection



HIWTF selection is a group multiple criteria decision making (GMCDM) problem, which may be described by means of the following sets (Sanayei et al., 2010):

1 a set of K decision makers called $E = \{D_1, D_2, \ldots, D_K\}$
2 a set of m possible transportation firms called $A = \{A_1, A_2, \ldots, A_m\}$
3 a set of n criteria, $C = \{C_1, C_2, \ldots, C_n\}$, with which transportation firms performances are measured
4 a set of performance ratings of A_i ($i = 1, 2, \ldots, m$) with respect to criteria C_j ($j = 1, 2, \ldots, n$), called $X = \{x_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\}$.

The main steps of the algorithms are taken from Sanayei et al. (2010) and Yücenur and Demirel (2012) study.

4.1 Identify the objectives of the decision making process and define the problem scope

Decision making is the process of defining the decision goals, gathering relevant information and selecting the optimal alternative. Thus, the first step is defining the decision goal that here is to evaluate and select a favourable transportation firms. Making precise statement of the problem will help to narrow it. Giving clear and careful thought to this first step is very vital to selecting process. The way in which the process is defined will deterministic the character of all the other steps.

In this step, the scope of the problem is defined in terms of the company's various needs (for example, Hygiene and safety, low logistics price, good customer service, etc.) in the HIWTF selection process. Then the objective of HIWTF selection is derived with the overall organisational goals.

4.2 Arrange the decision making group and define and describe a finite set of relevant attributes

In HIWTF evaluation and selection process several people and experts from different functional areas within the company are involved. So with considering the problem scope defined in previous section and its entire dimension, a Delphi group of decision makers are formed.

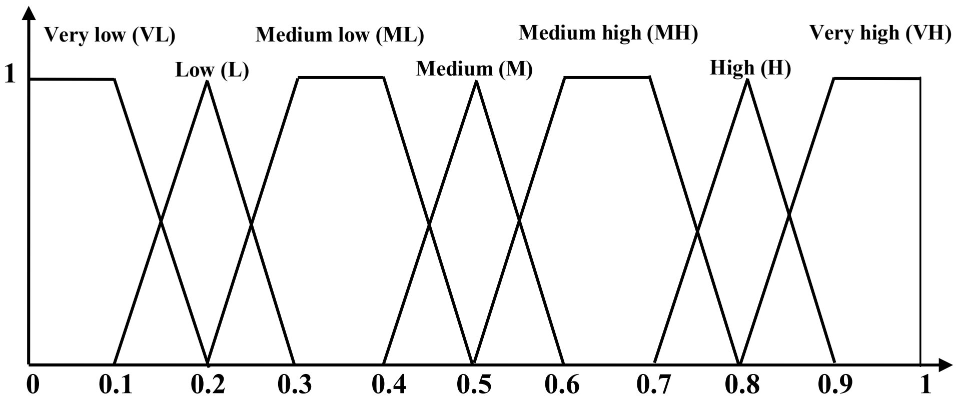
HIWTF selection first requires identification of decision attributes (criteria) then evaluation scales/metrics are determined in order to measure appositeness of transportation firms. Then with considering sub-criteria for each main criterion, hierarchical form called 'value tree' is structured.

4.3 Identify the appropriate linguistic variables

In this paper the importance weights of various criteria and the ratings of qualitative criteria are considered as linguistic variables. Because linguistic assessments merely approximate the subjective judgment of decision makers, it can consider that linear trapezoidal membership functions to be adequate for capturing the vagueness of these linguistic assessments (Sanayei et al., 2010).

The decision makers of Delphi group use the linguistic variables in positive trapezoidal fuzzy numbers shown in Figure 3 to evaluate the importance of the criteria and the ratings of alternatives with respect to qualitative criteria (Sanayei et al., 2010; Yücenur and Demirel, 2012).

Figure 3 Linguistic variables for importance weight of criteria



For example, the linguistic variable 'Medium Low (ML)' can be represented as (0.2, 0.3, 0.4, 0.5), the membership function of which is:

$$\mu_{Medium\ low}(x) = \begin{cases} 0, & x < 0.2, \\ \dfrac{x - a_1}{a_2 - a_1} & 0.2 \le x \le 0.3, \\ 1, & 0.3 \le x \le 0.4, \\ \dfrac{x - a_4}{a_3 - a_4} & 0.4 \le x \le 0.5, \\ 0, & x > 0.5, \end{cases} \tag{10}$$

4.4 Pull the decision makers' opinions to get the aggregated fuzzy weight of criteria, and aggregated fuzzy rating of alternatives and construct a fuzzy decision matrix

Let the fuzzy rating and importance weight of the k^{th} decision maker be $\tilde{x}_{ijk} = (x_{ijk1}, x_{ijk2}, x_{ijk3}, x_{ijk4})$ and $\tilde{w}_{jk} = (w_{jk1}, w_{jk2}, w_{jk3}, w_{jk4})$; $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$ respectively. Hence, the aggregated fuzzy ratings $\tilde{x}_{ij}$ of alternatives with respect to each criterion can be calculated as:

$$\tilde{x}_{ij} = \left(x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4}\right), \tag{11}$$

where

$$x_{ij1} = \min_k \{x_{ijk1}\},$$

$$x_{ij2} = \frac{1}{K}\sum_{k=1}^{K} x_{ijk2},$$

$$x_{ij3} = \frac{1}{K}\sum_{k=1}^{K} x_{ijk3},$$

$$x_{ij4} = \min_k \{x_{ijk4}\}$$

The aggregated fuzzy weights $\tilde{w}_j$ of each criterion can be calculated as:

$$\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4}) \tag{12}$$

where

$$w_{j1} = \min_k \{w_{jk1}\},$$

$$w_{j2} = \frac{1}{K}\sum_{k=1}^{K} w_{jk2},$$

$$w_{j3} = \frac{1}{K}\sum_{k=1}^{K} w_{jk3},$$

$$w_{j4} = \min_k \{w_{jk4}\}$$

A HIWTF selection problem can be concisely expressed in matrix format as follows:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{11} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}$$

$$\tilde{w} = [\tilde{w}_1 \quad \tilde{w}_2 \quad \dots \quad \tilde{w}_n]$$

where $\tilde{x}_{ij}$ the rating of alternative A_i with respect to C_j; $\tilde{w}_j$ the importance weight of the j^{th} criterion holds, $\tilde{x}_{ij} = (x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4})$ and $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$; $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$ are linguistic variables can be approximated by positive trapezoidal fuzzy numbers.

4.5 Defuzzify the fuzzy decision matrix and fuzzy weight of each criterion into crisp values

Deffuzzified fuzzy decision matrix and fuzzy weight of each criterion into crisp values using COA defuzzification relation proposed in equation (9).

4.6 *Determine the best f_j^* and the worst f_j^- values of all criterion ratings, j = 1, 2, …., n*

$$f_j^* = \min_i x_{ij} \tag{13}$$

$$f_j^- = \min_i x_{ij} \tag{14}$$

4.7 *Compute the values S_i and R_i by the relations*

$$S_i = \sum_{i=1}^{n} w_i \left(f_i^* - f_{ij}\right) \Big/ \left(f_j^* - f_j^-\right) \tag{15}$$

$$R_i = \max_j w_j \left(f_i^* - f_{ij}\right) \Big/ \left(f_j^* - f_j^-\right) \tag{16}$$

4.8 *Compute the values Q_i by the relations*

$$Q_j = v\left(S_i - S^*\right) \Big/ \left(S^- - S^*\right) + (1-v)\left(R_i - R^*\right) \Big/ \left(R^- - R^*\right) \tag{17}$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$, and v is introduced as a weight for the strategy of maximum group utility, whereas $1 - v$ is the weight of the individual regret.

4.9 *Rank the alternatives, sorting by the values S; R and Q in ascending order*

4.10 *Propose as a compromise solution the alternative ($A^{(1)}$) which is the best ranked by the measure Q (minimum) if the following two conditions are satisfied*

C1 Acceptable advantage:

$$Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) \geq DQ \tag{18}$$

where $A^{(2)}$ is the alternative with second position in the ranking list by Q;
$DQ = 1/(J - 1)$.

C2 Acceptable stability in decision making: The alternative $A^{(1)}$ must also be the best ranked by S or/and R. This compromise solution is stable within a decision making process, which could be the strategy of maximum group utility (when $v > 0.5$ is needed), or 'by consensus' $v \approx 0.5$, or 'with veto' ($v < 0.5$). Here, v is the weight of decision making strategy of maximum group utility.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of

- alternatives $A^{(1)}$ and $A^{(2)}$ if only the condition C2 is not satisfied
- alternatives $A^{(1)}$, $A^{(1)}$,…., $A^{(M)}$ if the condition C1 is not satisfied; $A^{(M)}$ is determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < DQ$ for maximum M (the positions of these alternatives are 'in closeness').

5 Application of the proposed methodology

In order to demonstrate the applicability of the proposed approach, it was tested on an automotive battery manufacturing company situated in the southern part of Bangladesh and having more than one decade of successful operations. The company, which began automotive battery manufacturing in the mid 1990s, was one of the largest automotive battery manufacturing plant in Bangladesh, producing 1,350 units of assorted batteries per week. It produced about 125 metric tons of hazardous solid waste; slag, which contained about 5%–6% lead, a highly toxic metal. As a condition of obtaining access for data collection, this study was unable to mention the real name of the organisation under investigation. This is because of sensitivity of data collection from this organisation.

Until 2011 the company used their own transportation system to cart away the slag for disposal in government approved sites. Due to the complaints of human health problems and death of livestock by communities affected by the improper disposal of the slag, government approved waste disposal site has been shifted and government ordered the company to dispense with the services of the waste contractors and to dispose the industrial hazardous solid waste into a constructed engineered landfill which is located about 89 kilometres away from the company. Recently the organisation is also trying to increase the overall production. That is why the automotive battery manufacturing company is willing to transport all the industrial hazardous solid waste and slag by a hazardous industrial waste transportation service provider firm. The company's goal is to select the best HIWTF which can satisfy the company's various needs (for example, Hygiene and safety, low logistics price, good customer service, etc.). In the following section, the detailed HIWTF selection process for the company is described.

Step 1: The organisation desires to select the suitable and effective HIWTFs for getting better competitive advantages. After preliminary screening, five transportation firms (TF1, TF2, TF3, TF4, TF5) remain for further evaluation.

Step 2: The three decision makers (DM1, DM2 and DM3) of the Delphi group identified five most appropriate and important criteria for final evaluation. Those are:

1 compatibility

2 technical capability

3 hygiene and safety

4 cost of service

5 work experience in related field.

Step 3: Three decision makers use the linguistic weighting variables shown in Figure 3 to assess the importance of the criteria. The importance weights of the criteria determined by these three decision makers are shown in Table 1. Also the decision makers use the linguistic rating variables shown in Figure 3 to evaluate the ratings of candidates with respect to each criterion. The ratings of the transportation firm alternatives by the decision makers under the various criteria are shown in Table 2.

Table 1 Importance weight of criteria from three decision makers

Criteria	*Decision makers*		
	DM1	*DM2*	*DM3*
C1	H	VH	VH
C2	M	MH	M
C3	MH	H	H
C4	M	MH	MH
C5	MH	MH	H

Table 2 Ratings of the five transportation firms by the decision makers under the various criteria

Decision makers	*Alternatives*	*Criteria*				
		C1	*C2*	*C3*	*C4*	*C5*
DM1	TF1	M	ML	H	H	H
	TF2	VH	MH	L	M	L
	TF3	MH	MH	VH	VH	M
	TF4	VL	L	H	MH	H
	TF5	L	H	VH	H	L
DM2	T1	M	M	H	MH	H
	T2	VH	MH	L	M	ML
	T3	MH	MH	VH	VH	M
	T4	VL	ML	H	MH	H
	T5	L	H	H	H	VL
DM3	T1	M	ML	H	MH	H
	T2	H	MH	ML	M	L
	T3	H	H	VH	VH	M
	T4	L	L	H	MH	H
	T5	ML	H	VH	MH	VL

Step 4: The linguistic evaluations shown in Tables 1 and 2 are converted into trapezoidal fuzzy numbers. Then the aggregated weight of criteria and aggregated fuzzy rating of transportation firms is calculated to construct the fuzzy decision matrix and determine the fuzzy weight of each criterion, as in Table 3.

Table 3 Aggregated fuzzy weight of criteria and aggregated fuzzy rating of alternatives

	Criteria				
	C1	*C2*	*C3*	*C4*	*C5*
Weights	0.7, 0.83, 0.87, 1.0	0.4, 0.53, 0.57, 0.8	0.5, 0.73, 0.77, 0.9	0.4, 0.57, 0.67, 0.8	0.5, 0.67, 0.73, 0.9
TF1	0.4, 0.5, 0.5, 0.6	0.2, 0.37, 0.43, 0.6	0.7, 0.8, 0.8, 0.9	0.5, 0.67, 0.73, 0.9	0.7, 0.8, 0.8, 0.9
TF2	0.7, 0.87, 0.93, 1.0	0.5, 0.6, 0.7, 0.8	0.1, 0.23, 0.27, 0.5	0.4, 0.5, 0.5, 0.6	0.1, 0.23, 0.27, 0.5
TF3	0.5, 0.67, 0.73, 0.9	0.5, 0.67, 0.73, 0.9	0.8, 0.9, 1.0, 1.0	0.8, 0.9, 1.0, 1.0	0.4, 0.5, 0.5, 0.6
TF4	0.0, 0.07, 0.13, 0.30	0.1, 0.23, 0.27, 0.5	0.7, 0.8, 0.8, 0.9	0.5, 0.6, 0.7, 0.8	0.7, 0.8, 0.8, 0.9
TF5	0.1, 0.23, 0.27, 0.5	0.7, 0.8, 0.8, 0.9	0.7, 0.87, 0.93, 1.0	0.3, 0.73, 0.77, 0.9	0.0, 0.07, 0.13, 0.30

Step 5: The crisp values for decision matrix and weight of each criterion are computed as shown in Table 4.

Table 4 Crisp values for decision matrix and weight of each criterion

	Criteria				
	C1	*C2*	*C3*	*C4*	*C5*
Weights	0.85	0.57	0.72	0.60	0.70
TF1	0.50	0.40	0.80	0.70	0.80
TF2	0.87	0.65	0.27	0.50	0.27
TF3	0.70	0.70	0.92	0.92	0.50
TF4	0.12	0.27	0.80	0.65	0.80
TF5	0.27	0.80	0.87	0.65	0.12

Step 6: The best and the worst values of all criterion ratings are determined as follows:

f^*	0.87	0.8	0.92	0.92	0.8
f^-	0.12	0.27	0.27	0.5	0.12

Steps 7 and 8: The values of S, R and Q are calculated for all transportation firms as Table 5.

Step 9: The ranking of the transportation firms by S, R and Q in decreasing order is shown in Table 6.

Table 5 The values of S, R and Q for all alternatives

	Alternatives				
	TF1	*TF1*	*TF1*	*TF1*	*TF1*
S	1.297	2.027	0.609	1.939	1.821
R	0.430	0.720	0.309	0.850	0.700
Q	0.355	0.880	0	0.969	0.789

Table 6 The ranking of the alternatives by S, R and Q in decreasing order

	Ranking alternatives				
	1	*1*	*1*	*1*	*1*
S	TF3	TF1	TF5	TF4	TF2
R	TF3	TF1	TF5	TF2	TF4
Q	TF3	TF1	TF5	TF2	TF4

Step 10: According to the Q value, TF3 is the most appropriate and effective transportation firm for the organisation (Table 6). Also the conditions C1 and C2 are satisfied ($Q_{TF1} - Q_{TF3} \geq 1/5\text{-}1$ and TF3 is best ranked by R and S). So transportation firm TF3 is the best choice for the organisation followed by TF1 and TF5.

6 Conclusions

The hazardous industrial waste transportation service provider firm selection problem is often influenced by uncertainty in practice and in real life decision making process, the decision maker is unable (or unwilling) to express his/her preferences precisely in numerical values and the evaluations are very often expressed in linguistic terms. In such situation fuzzy set theory is an appropriate tool to deal with this kind of problems. In this study, the HIWTF evaluation problem is handled through integrating extended VIKOR method with fuzzy set theory.

It appears this method has some advantages which may be useful in dealing with HIWTF selection problem. The proposed method is very flexible. The proposed method can consider any number of quantitative and qualitative HIWTF selection attributes simultaneously and offers a more objective and reliable HIWTF selection approach. Using this method not only enables us to determine the outranking order of HIW transportation firms, but also assess and rate the firms. Also the proposed method for HIWTF selection in fuzzy environment provides a systematic approach which can be easily extend to deal with other management decision making problems, e.g., selecting the transportation firm for medical waste, selecting the contractors for construction work, selection of the vendors to supply the components, selecting the partner for any services which are to be outsourced by an organisation.

As research limitations, only five criteria have been chosen for the analysis. To get more effective decision, firm evaluation criteria number can be increased and detailed by sub-criteria. Also, a sensitivity analysis can performed to discuss and to check the stability of the results. For the future research, other decision-making methods can be included in the methodology to ensure more integrated and/or comparative study. The results of this study can be compared with that of other multi-criteria techniques like TOPSIS, ELECTRE, PROMETHEE. And a user friendly interface can be prepared to speed up and simplify the calculations.

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