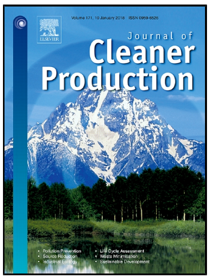

Analysis and prioritisation of risks in a reverse logistics network using hybrid multi-criteria decision making methods

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Highlights

- Risks involved in reverse logistics are analyzed and prioritized using hybrid methods
- Managers get an insight of risks in reverse logistics and understand their relative importance.
- Risk prioritization is conducted for a case company recycling PET bottles.
- Managing Inventory has a big impact on reverse logistics.

Analysis and prioritisation of risks in a reverse logistics network using hybrid multi-criteria decision making methods

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Abstract

Strict environmental regulations and diminishing raw material resources have strengthened the importance of reverse logistics at an increasing rate. However a substantial amount of risk is involved in the reverse supply chain which has to be managed by organizations effectively. The risks associated with reverse logistics have however not been addressed appropriately. In response to this knowledge gap, this study aims to prioritize the risks in reverse logistics Risk prioritization is a multi-criteria decision making (MCDM) problem. In this work, risks involved in reverse logistics are prioritized using hybrid multi-criteria decision making methods. A case of plastic recycling firm is discussed for the illustration of the approach. The major contribution of this work lies in the development of linkages among the various functions in reverse logistics. The results indicate that managing inventory has a significant impact on reverse logistics. It was observed that social concern with respect to protecting the environment in general is based on the cooperation of customers. The findings of the study will provide useful insight to the supply chain managers and researchers for decision-making in reverse logistics.

Keywords: Reverse logistics, Risk prioritization, Multi-criteria decision making.

1. Introduction

Reverse Logistics (RL) focus on how to take back the returns and recover them efficiently and economically. Over the last decade reverse logistics had a significant economic impact on industry as well as society (Krumwiede and Sheu, 2002). Proper handling or returns also has important customer service implications. The existence, effectiveness and efficiency of service management activities such as repair services and value recovery depend heavily on effective RL operations (Tibben –Lembke and Rogers, 2002). The effective management of RL operations increases profitability. Recycling is a product recovery option that involves techniques for creating new materials from wastes. Chen et al. (2007) observed recycling as a sub-process within reverse logistics to reduce the solid waste volume generated by the disposition of consumer products normally at the end of product's life-span or due to defect. Both recycling stations and centers will increase their market share and become integrated to the whole remanufacturing industry by collaborating with remanufacturing businesses (Zhang et al., 2017). The advantages of recycled materials are that they generally have a lower carbon footprint than raw materials converted into finished goods through a carbon intensive process (Ravi, 2012). Bing et al. (2015) re-design a reverse supply chain from a global angle on household plastic waste distributed from Europe to China. Klausner and Hendrickson

(2000) suggested that firms combine recycling operations with reusing or remanufacturing operations in order to stay profitable.

Plastic recycling is a legal requirement and can yield environmental benefits. Wong (2010) confirmed that the recycling of post-consumer plastics has less environmental impact than the use of crude oil to produce virgin plastics. However, plastic collection practices vary in different countries which have an impact on the network structure of reverse logistics for plastic waste. The CO_2 emissions due to the production of virgin polymer are 6 kg per kg of polymer while it is 3.5 kg for that of recycled plastics (Wong, 2010). Polyethylene Teraphalathate (PET) is used as a raw material for making bottles for packaging soft drinks, alcoholic beverages, detergents, cosmetics, pharmaceutical products and edible oils.

In recent years, supply chains have become increasingly vulnerable to disruptions. Earthquakes, tsunamis, fires, explosions and terrorism are a few examples of events that make catastrophic implications for both larger organisations and small and medium-sized enterprises (SMEs). These events highlight the nature of risk and create a need for organisations to develop subsequently appropriate capabilities toward overcoming their occurrence.

Some researchers have developed certain tools to enumerate and manage the risks involved in forward logistics. Most research focuses only on a small area of RL systems, such as network design, production planning or environmental issues. However, there is almost no research on risk management in reverse logistics. There is hardly any literature on the PET bottle reverse logistics system in India. The present research aims to fill this gap and to explore the opportunities for improved economic gain. The objectives of this paper are as follows:

- To analyse the different types of risks or potential risks in reverse logistics
- To apply Analytical Hierarchy Process (AHP) combined with Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) for prioritising the reverse logistics risks.
- To validate the obtained prioritisation ranking using digraph and matrix method.

The rest of the paper is structured as follows: Section 2 provides a review of the relevant literature. Section 3 describes the problem. Section 4 presents the methodology used to develop the framework. Section 5 presents an application of the methodology to a case study. Managerial implications are presented in Section 6. Finally, conclusion is presented in Section 7.

2. Literature Review

A growing number of companies have begun to realize the importance of implementation of integrated supply chain management (Kannan, 2009). Task of developing reverse logistics and closed-loop supply chains in both developed and developing industries is accepted as a vital need in our societies (Govindan and Soleimani, 2017). Decision making in reverse logistics operations involves the type of recovery to perform for returns, the location to perform recovery, the mode of transportation, and the pricing for the recovered parts. Jabbour et al. (2013) indicated that environmental management is influenced by human resource management and lean manufacturing. Giannetti et al. (2013) indicated that recycling networks requires appropriate logistical structures for managing the reverse flow of materials from users to producers.

The literature review is presented in two parts; the first part deals with the literature on reverse logistics and the second part deals with risk management in logistics.

2.1 Reverse logistics

Reverse logistics is a part of a broader supply chain management process called returns management. Logistics network design problems that take into account the facility locations and the shipment of the product flows have been analysed in the past. Sudarto et al. (2016) analyzed the impact of capacity planning on the product lifecycle for performance on sustainability dimensions in reverse logistics. Mangla et al. (2016) evaluated the critical success factors linked to the implementation of RL in manufacturing industries in India. Guarineri (2015) proposed a conceptual framework to help decision makers and researchers in performing a multicriteria decision analysis in the area of third party reverse logistics provider selection. Nikolaou et al. (2013) proposed an integrated model for introducing Corporate Social Responsibility (CSR) and sustainability issues in reverse logistics systems as a means of developing a complete performance framework.

Bai and Sarkis (2013) introduced a reverse logistics flexibility framework by including both operational and strategic flexibilities. El-Sayed et al. (2010) developed a multi-period multi-echelon forward–reverse logistics network design under risk. The proposed network structure consists of three echelons in the forward direction and two echelons, in the reverse direction.

Rahman and Subramanian (2012) used the cognition mapping process to identify the critical factors in designing and implementing end-of-life (EOL) computer recycling operations in reverse logistics. Kannan et al. (2015) proposed a multi-criteria decision-making (MCDM) approach called Fuzzy Axiomatic Design (FAD) to select the best green supplier for plastic manufacturing company. Most of the research focuses only on the technical issues such as network design and inventory management. Risk involved in the reverse logistics and distribution of the returned products is not considered.

2.2 Risk management

Researchers identified that supply chain risks are not addressed with due importance (Tang, 2006; Harrington and O'Connor, 2009). To select the appropriate robustness measure and to tailor the mitigation approaches, the supply chain risks are to be prioritised. Nokia and Eriksson were subjected to risk during the year 2000 when a fire destroyed an electronics plant in New Mexico. Both the companies were supplied with the electronic components by the same plant. Nokia fulfilled all its requirements upfront by getting the components from other suppliers but Eriksson did not react the same way and were not prepared for any kind of uncertainty or risk and suffered a major loss of $390M (Basu et al., 2007).

Lintukangas et al. (2016) investigated the firm's ability to mitigate different types of supply risks related to the company's adoption of green supply management. Sheu (2008) examined the factors such as the operational risks induced in both the power generation and reverse logistics processes for the model formulation. Ramanathan (2010) showed that logistics performance and customer loyalties are affected by risk characteristics of products and efficiencies. Subramanian and Rahman (2014) analysed the complexity issues and appropriate strategies for the supply chain and propose an alignment model to mitigate complexities using material flow and contractual relationship strategies. Cucuzzella (2016) highlighted the approaches for addressing sustainability and creating the link with the risk management.

Despite increasing awareness among practitioners, the concepts of supply chain vulnerability and its managerial counterpart supply chain risk management are still in their infancy (Juttner et al., 2003). Trkman and McCormack (2009) presented preliminary research concepts regarding a new approach to the identification and prediction of supply risk. This approach to the assessment and classification of suppliers is based on supplier's attributes, performances and supply chain characteristics, while it is also modified by factors in the supplier's specific environment.

In general, supply chains have become increasingly vulnerable to disruptions (Tang, 2006; Min and Kim, 2011). Managing risk is a complex and challenging task as the individual risks are interconnected and actions that mitigate one risk can end up exacerbating another (Chopra and Sodhi, 2012; Pfohl et al., 2010). In recent years, risks have grown significantly and it is necessary to include other criteria such as cost of recourse after interruption, business recovery time and environmental issues for assessing the severity (Klibi et al., 2010). Supply chain risk management (SCRM) plays a major role in managing the business processes in a positive manner (Lavastre et al., 2012). The literature review on SCRM process is summarised in Table 1.

“Insert Table 1 here’’

The current reverse logistics in general does not have risk management function. Further, research is required for the prioritisation of risk in reverse logistics for product recovery network. The existing risk prioritisation methods such as failure mode effect analysis (FMEA), Johnson analysis and Bayesian network are limited for assigning the criteria weights. In the present research, Analytical Hierarchy Process (AHP) combined with Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and

Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) are proposed for prioritizing the reverse logistics risk. The details of the study are presented in the following sections.

3. Problem Definition

Risk management is an integral component of a successful organisation's strategy and operation. It is a structured approach of identifying, mitigating and assessing risks to reduce losses. It includes three steps namely risk identification, risk mitigation and risk evaluation and assessment. A prioritization process is followed whereby the risks with the greatest loss and the greatest probability of occurring are handled first, and risks with lower probability of occurrence and lower loss are handled in descending order. The risks can be categorized as internal risks and external risk. The internal risks in reverse logistics include inventory risk, data managing risk, time management risk. The external risks are the ones where the system interacts with external environment such as environmental risk and outsourcing risk. The review of the literature on risk management in reverse logistics led to the identification of major gaps. First, no definition exists that adequately takes into account the unique dimensions of risk and risk management in a global reverse logistics. Instead there are a multitude of definitions which results in confusion between terms such as risks, uncertainties, vulnerabilities, and sources of risks. In the present research, risk prioritization is conducted for a case company recycling PET bottles.

3.1 Risk Identification

Risk identification aims on finding the risks that have an impact on the industry. A risk management plan that addresses the what, when, where, why, who and how is developed.

The next step is identification of root cause where the causes of risks are identified and defined. For a clear understanding, a Strength, Weakness, Opportunity, and Threat (SWOT) analysis is performed to find the strengths, weaknesses, opportunities and threats. The various risks indicated in the literature are shown in Table 2.

‘‘Insert Table 2 here’’

By personal interview with the company personnel, the various risks involved in reverse logistics are identified as follows:

Environmental risk (A1): Risks associated with damage to the environment and resistance from local community.

Inventory risk (A2): Risks involved with storage problem in terms of space, storage conditions, damaged products, and damage in storage.

Data managing risk (A3): Risk associated with accuracy of the information, security, disruption, intellectual property and information outsourcing.

Time Management risk (A4): Risk which arises due to sorting delays and less manpower.

Managerial risk (A5): This arises due to lack of consistency plan, lack of expertise and experience.

Cultural risk (A6): This arises due to the resistance to apply new methods.

Quantity risk (A7): Risk that the desired quantity of an item may not be available for purchase.

Outsourcing risk (A8): Risk associated with damage in transportation, errors from third party reverse logistics provider (3PRLP), and unknown hidden cost.

Disruption/catastrophic risk (A9): It refers to the natural and man-made disasters such as earthquakes, flood, epidemic, labour strike, accidents and terrorist attacks.

Based on the literature survey and with the validation from industrial experts, possible evaluation criteria for prioritisation of risks are defined and given in Table 3. The decision makers use the linguistic assessment to rate the criteria and the alternatives.

‘‘Insert Table 3 here’’

3.2 Problem Description

The main objective of this research is to develop a methodology for the prioritisation of reverse logistics risks. Prioritising the risk in reverse logistics network is treated as a multi-criteria decision making problem in which the decision maker treats the highly ranked priority as the important one. In this work, Analytical Hierarchy Process (AHP) combined with Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is proposed for prioritising the risk in reverse logistics. Once the risks in reverse logistics are prioritised, the appropriate robustness measure can be taken and the mitigation approaches can be performed.

4. Proposed Methodology

Multi-criteria decision making is employed to solve the problems which involve selecting from a finite number of alternatives. A multi-criteria decision making method (MCDM) ranks the alternatives and the highest ranked one is recommended as the best alternative to the decision maker. Each decision table in MCDM methods has four main parts, namely: (a) alternatives, (b) criteria, (c) weight or relative importance of each attribute, and (d) measures of performance of alternatives with respect to the attributes.

One of the main characteristics of reverse logistics is its uncertainties in many aspects. These uncertainties appear throughout every activity in the reverse logistics. As the risk prioritisation problem involves multiple conflicting criteria with a finite set of candidate alternatives, MCDM methods can be effectively used to solve such type of problem.

The detailed flow chart of the proposed method is explained in Fig. 1.

''Insert Fig. 1. Here''

In this paper, the following hybrid MCDM methods are considered to compare the performance of different MCDM methods:

- Hybrid AHP - Fuzzy TOPSIS method (Hybridisation of AHP with Fuzzy TOPSIS)
- Hybrid AHP - PROMETHEE method (Hybridisation of AHP with PROMETHEE)
- Hybrid AHP - Diagraph and Matrix method (Hybridisation of AHP with Diagraph and Matrix)

These methods are briefly described as follows.

4.1 Analytical Hierarchy Process

Analytic Hierarchy Process enables decision makers to structure complex problems in a simple hierarchical form and to evaluate a large number of factors in a systematic way. AHP is a powerful and flexible decision-making process to help managers set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered (Saaty, 2000). AHP is a more systematic method and is capable of capturing a human appraisal of ambiguity when complex multi-criteria decision making problems are considered (Kannan and Murugesan, 2011).

The first step involves selection of criteria for prioritising the risks. After discussion with the company and based on the literature review, the criteria are selected.

The procedure of the AHP method for risk prioritisation is explained as follows.

4.1.1. Decision hierarchy development and determination of goal

A hierarchical structure is developed with the goal at the top level, the criteria at the second level and alternatives at the third level.

4.1.2 Establishment of pairwise comparison matrix

AHP uses pairwise comparison of a decision maker to determine the importance of criteria in a decision. Because most criteria are intangible, it is also important to compare the alternatives with respect to each such criterion. The numerical judgments use the fundamental scale of absolute numbers from 1 to 9, as presented in Table 4.

''Insert Table 4 here''

4.1.3 Determination of consistency by calculating the Eigen vectors

The weight of each attribute is determined by calculating the geometric mean of the row and then normalizing the geometric means of rows in comparison matrix. Consistency index (CI) is determined using the following equation:

$$CI = \frac{(\lambda_{\max} - M)}{(M - 1)} \qquad (1)$$

Consistency ratio (*CR*) is calculated using the relation

$$CR = CI / RI \tag{2}$$

Where $\lambda_{\max}$ = Maximum Eigen value

CI = Consistency Index

RI = Random Index

The values of random index are obtained from Table 5.

‘‘Insert Table 5 Here’’

If the value of CR is below the threshold of 0.1, then the evaluation of the importance of customer requirements is considered to be reasonable. If the final consistency ratio exceeds this value, the evaluation procedure has to be repeated to improve consistency. The measurement of consistency is used to evaluate the consistency of decision-makers as well as the consistency of overall hierarchy. In many practical cases, the human preference model is uncertain and decision-makers might be reluctant or unable to assign crisp values to the comparison judgments. Though a scale of 1 to 9 is used, this method cannot deal with decision-makers’ ambiguities, uncertainties and vagueness which cannot be handled by crisp values. To overcome the uncertainty, fuzzy multiple criteria decision making methods are incorporated. The use of fuzzy set theory (Zadeh, 1965) allows the decision-makers to incorporate unquantifiable information, incomplete information; non-obtainable information and partially ignorant facts into decision.

4.2 Fuzzy TOPSIS method

The technique for order preference by similarity to an ideal solution (TOPSIS) method is based on the principle that the chosen alternative should have the shortest distance from the ideal solution and the longest distance from the negative ideal solution. The ideal solution is a solution that maximizes the benefit criteria and minimizes the cost criteria. Though trapezoidal fuzzy number can be used in some cases, triangular fuzzy numbers are preferred in TOPSIS because of its simplicity and ease of use. Modelling using triangular fuzzy numbers has proven to be an effective way for formulating decision problems where the information available is subjective and imprecise (Kahraman et al., 2004). Some basic definitions of fuzzy sets are given below (Onut & Soner, 2008):

Definition 1. A fuzzy set $\tilde{A}$ in a universe of discourse X is characterized by a membership function $\tilde{\mu}_A(x)$ which associates with each element *x* in *X*, a real number in the interval [0, 1]. The function value is termed the grade of membership of *x* in $\tilde{A}$.

Definition 2. A triangular fuzzy number is characterized by a triple of real numbers (a_1, a_2, a_3) where a_2 indicates the value of membership function, a_1 and a_3 represent the lower and upper bound.

$$\mu(x) = \begin{cases} 0, x \le a_1 \\ \dfrac{x-a_1}{a_2-a_1}, a_1 \le x \le a_2 \\ \dfrac{x-a_3}{a_2-a_3}, a_2 \le x \le a_3 \\ 0, x \ge a3 \end{cases} \tag{3}$$

If $\tilde{A}$ and $\tilde{B}$ be two triangular fuzzy numbers defined by (a_1, a_2, a_3) and (b_1, b_2, b_3), then the operational laws of these triangular numbers are as follows

$$\tilde{A}(+)\tilde{B} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{4}$$

$$\tilde{A}(-)\tilde{B} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \tag{5}$$

$$\tilde{A}(\times)\tilde{B} = (a_1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1.b_1, a_2.b_2, a_3.b_3) \tag{6}$$

$$\tilde{A}(\times)\tilde{B}=(a_1,a_2,a_3)(\times)(b_1,b_2,b_3)=\left(a_1/b_3,a_2/b_2,a_3/b_3\right) \quad (7)$$

$$K\tilde{A}=\left(ka_1,ka_2,ka_3,ka_4\right) \quad (8)$$

$$\left(\tilde{A}\right)^{-1}=\left(1/a_3,1/a_2,1/a_1\right) \quad (9)$$

Definition 3. If $\tilde{a}=(a_1,a_2,a_3)$ and $\tilde{b}=(b_1,b_2,b_3)$ be the two triangular numbers, then the distance between them is calculated using the vertex method.

$$d\left(\tilde{a},\tilde{b}\right)=\sqrt{\frac{1}{3}\left[(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2\right]} \quad (10)$$

*Definition 4.*The weighed normalized fuzzy decision matrix is obtained using

$$\tilde{V}=\left[\tilde{v}_{ij}\right]_{n\times J} \qquad i=1,2,\ldots,M \qquad j=1,2,\ldots,J \quad (11)$$

where $\tilde{v}_{ij}=\tilde{x}_{ij}\times w_i$.

Based on the above definitions, the various steps in fuzzy TOPSIS are as follows:

Step 1: Determine the linguistic values $(x_{ij}, i=1,2,\ldots,n, J=1,2,\ldots,J)$ for alternatives with respect to criteria. The fuzzy linguistic rating (x_{ij}) preserves the property that the range of normalized triangular fuzzy numbers belonging to (0, 1) .There is no need for normalization.

Step 2: The weighted normalised decision matrix can be computed by multiplying the importance weights of evaluation criteria and the values in the normalised fuzzy decision matrix. The weighed normalized value is calculated using equation (11).

Step 3: The positive ideal and negative ideal solutions are identified using equations 12 and 13.

$$A^{+} = \{v_1^{+}, v_2^{+}, \ldots, v_i^{+}\} = \{(\max v_{ij} \mid i \in I') \times (\min v_{ij} \mid i \in I'')\} \quad i=1,\ 2, \ldots,\ M \quad j=1,2, \ldots, J \qquad (12)$$

$$A^{-} = \{v_1^{-}, v_2^{-}, \ldots, v_i^{-}\} = \{(\min v_{ij} \mid i \in I') \times (\max v_{ij} \mid i \in I'')\} \quad i=1,\ 2, \ldots,\ M \quad j=1,2, \ldots, J \qquad (13)$$

Where I' is associated with the benefit criteria and I'' is associated with the cost criteria.

Step 4: The Euclidean distance between positive ideal solution and negative ideal solution for each alternative is calculated.

$$D_j^{+} = \sum_{j=1}^{n} d(v_{ij}, v_i^{+}) \qquad j = 1,2,\ldots,J \qquad (14)$$

$$D_j^{-} = \sum_{j=1}^{n} d(v_{ij}, v_i^{-}) \qquad j = 1,2,\ldots,J \qquad (15)$$

Step 5: The final step combines the two distances in order to obtain the relative coefficient closeness by the following equation.

$$CCj = \frac{D_j^{+}}{D_j^{-} + D_j^{+}} \qquad j = 1,2,\ldots,J \qquad (16)$$

Step 6: According to the closeness coefficient, one can understand the assessment status of each alternative and the ranking order of all alternatives can be determined.

4.3 Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)

PROMETHEE is an outranking method for ranking a finite set of alternative actions to be selected among criteria, which are often conflicting. The PROMETHEE method is one of the most recent MCDM method developed by Brans et al., (1986). PROMETHEE is also a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis. The PROMETHEE methods have some requisites of an appropriate multi-criteria method and their success is due to their mathematical properties and to their particular friendliness of use. For each criterion, the preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. The implementation of this method requires information on the relative importance or the weights of the criteria considered and information on the decision maker's preference function, which he/she uses when comparing the contribution of the alternatives in terms of each separate criterion. PROMETHEE method can effectively deal mainly with quantitative criteria. For qualitative criterion, a ranked value judgment on a fuzzy conversion scale is adopted in this paper. By using fuzzy set theory, the value of the criteria can be first decided as linguistic terms and then converted into corresponding fuzzy numbers.

The various steps in PROMETHEE can be outlined as follows (Venkata Rao and Patel, 2010):

The weights obtained from AHP can be utilized for all parameters. The preference function P_i converts the difference between the evaluations from two alternatives $b1$ and $b2$ into a preference degree ranging from 0 to 1.Taking the preference function associated with the criterion as P_{ib1b2}

$$P_{i,b1b2} = G_i[c_i(b1) - c_i(b2)] \tag{17}$$

$$0 \le P_{ib1b2} \le 1 \tag{18}$$

G_i is the non-decreasing function of the observed deviation between two alternatives over the criterion b_i. The multiple criteria preference index indicates the preference of decision maker b_1 over b_2 and is defined as the weighted average of the preference functions P_i. This preference index finds the outranking relation on the set of actions.

$$\prod_{b1b2}=\sum_{i=1}^{M} w_i P_{ib1b2} \qquad (19)$$

The leaving flow, entering flow and the net flow for an alternative *b* belonging to a set of alternatives *B* are defined by the following equations:

$$\varphi^{+}(b)=\sum_{x\in B}\Pi_{xb} \qquad (20)$$

$$\varphi^{-}(b)=\sum_{x\in B}\Pi_{bx} \qquad (21)$$

$$\varphi\ (b)=\varphi^{+}(b)-\varphi^{-}(b) \qquad (22)$$

4.4 Digraph and Matrix Methods

Graph theory is a natural and powerful tool in operation research, transport network, and the activity of stochastic processes useful for modelling and analysing various kinds of systems in fields of science and engineering. The most common representation is by means of digraph in which the vertices are represented as points, and each edge as a line segment joining its end vertices. This method has three constructs a) digraph representation for visual analysis, b) matrix representation for computer processing, and c) permanent representation suitable for expressing the effect of each variable by an index (Grover et al., 2006).

4.4.1 Reverse logistics risk prioritisation attribute digraph

A digraph is used to indicate the factors and their interrelationships in terms of nodes and edges. A digraph consists of a set of nodes ($i = 1, 2\ldots, M$) and a set of directed edges. A node n_i represents i th selection criterion and edges represent the relative importance among the criteria. The relative importance of a criterion *i* over another criterion *j* is represented by an arrow drawn from the node *i* to the node *j*. As the number of nodes and their interrelations increases, the digraph becomes complex. In such a case, the visual analysis of the diagraph is expected to be difficult and complex. To overcome this constraint, the digraph is represented in a matrix form.

4.4.2 Matrix representation

Representation of digraph by a matrix makes it easier for computer processing. The reverse logistics risk prioritisation performance attributes matrix is $M\ X\ M$ matrix which considers the presence of criteria (i.e. A_i) and their relative importance (a_{ij}) where, A_i is the value of i-th criterion represented by node n_i and a_{ij} is the relative importance of i-th criterion over j- th represented by the edge e_{ij}. If there are M numbers of selection criterion and relative importance exists between all of the attributes, then the selection attributes matrix A for the digraph is written as

$$\begin{array}{cc|ccccccc|} & \text{Criterion} & 1 & 2 & 3 & & & & M \\ & 1 & A_1 & a_{12} & a_{13} & . & . & . & a_{1M} \\ & 2 & a_{21} & A_2 & a_{23} & . & . & . & a_{2M} \\ & 3 & a_{31} & a_{32} & A_3 & . & . & . & a_{3M} \\ C = & . & . & . & . & . & . & . & . \\ & . & . & . & . & . & . & . & . \\ & . & . & . & . & . & . & . & . \\ & M & a_{M1} & a_{M2} & a_{M3} & . & . & . & A_M \end{array} \qquad (23)$$

Permanent of this matrix C, i.e. *per (C),* is defined as the evaluation index. The permanent function of the matrix is calculated in a similar manner as its determinant, but by changing all the negative signs that appear during determinant calculation to positive signs. No negative sign appear in the expression and no information will be lost (Rao and Padmanaban, 2007).

4.4.2 Evaluation index

The numerical value of evaluation index defined in equation (23) is called as evaluation index. When quantitative values of the attributes are available, normalized values of the attributes are calculated by v_{ij}/v_{il} where v_{ij} is the fuzzy value of criterion *i* over alternative *j* for *i*- th alternative and v_{il} is the fuzzy value of criterion i over alternative *l* which is having higher measure of the factor among the considered alternatives. This ratio is valid for beneficial factors only. For cost factor, the normalized values assigned to the alternatives are calculated by $v_{il}/v_{ij.}$ (Rao and Gandhi , 2002).

In equation form, the evaluation index is obtained as follows:

$$
\begin{aligned}
per(C) = {} & \prod_{i=1}^{M} A_i + \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (ai_j a_{ji}) A_k A_l A_m A_n A_o \ldots A_t A_m \\
& + \sum_{i=1}^{M-2} \sum_{j=i+1}^{M-1} \sum_{k=j+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{ki}) A_1 A_m A_n A_o \ldots A_t A_m \\
& + \Big(\sum_{i=1}^{M-3} \sum_{j=i+1}^{M} \sum_{k=i+1}^{M-1} \sum_{l=i+2}^{M} \cdots \sum_{M=t+1}^{M} (a_{ij} a_{ji})(a_{kl} a_{lk}) A_m A_n A_o \ldots A_t A_m \\
& + \sum_{i=1}^{M-3} \sum_{j=i+1}^{M-1} \sum_{k=i+1}^{M} \sum_{l=j+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{kl} a_{li} + a_{il} a_{lk} a_{kj} a_{ji}) A_m A_n A_o \ldots A_t A_m \Big) \\
& + \Big(\sum_{i=1}^{M-2} \sum_{j=i+1}^{M-1} \sum_{k=j+1}^{M} \sum_{l=1}^{M-1} \sum_{m=l+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{ki} + a_{ik} a_{kj} a_{ji})(a_{1m} a_{m1}) A_n A_o \ldots A_t A_m \\
& + \sum_{i=1}^{M-4} \sum_{j=i+1}^{M-1} \sum_{k=i+1}^{M} \sum_{l=i+1}^{M} \sum_{m=j+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{lm} a_{mi} + a_{im} a_{ml} a_{lk} a_{kj} a_{ji}) A_n A_o \ldots A_t A_M \Big) \\
& \Big(\sum_{i=1}^{M-3} \sum_{j=i+1}^{M-1} \sum_{k=i+1}^{M} \sum_{l=j+1}^{M} \sum_{m=1}^{M-1} \sum_{n=m+1}^{M} \cdots\cdots\cdots \sum (a_{ij} a_{jk} a_{kl} a_{li} + a_{il} a_{lk} a_{kj} a_{ji})(a_{mn} a_{nm}) A_o \ldots A_t A_m \\
& + \sum_{i=1}^{M-5} \sum_{j=i+1}^{M-1} \sum_{k=j+1}^{M} \sum_{l=1}^{M-2} \sum_{m=l+1}^{M-1} \sum_{n=m+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{ki} + a_{ik} a_{kj} a_{ji})(a_{im} a_{mn} a_{nl} + a_{in} a_{nm} a_{ml}) A_o \ldots A_t A_M \\
& + \sum_{i=1}^{M-5} \sum_{j=i+1}^{M} \sum_{k=i+1}^{M-3} \sum_{l=i+2}^{M} \sum_{m=k+1}^{M-1} \sum_{n=k+2}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{ji})(a_{kl} a_{lk})(a_{mn} a_{nm}) A_o \ldots A_t A_M \\
& + \sum_{i=1}^{M-5} \sum_{j=i+1}^{M-1} \sum_{k=i+1}^{M} \sum_{l=i+1}^{M} \sum_{m=i+1}^{M} \sum_{n=j+1}^{M} \cdots\cdots\cdots \sum_{M=t+1}^{M} (a_{ij} a_{jk} a_{kl} a_{lm} a_{mn} a_{ni} + a_{in} a_{nm} a_{ml} a_{lk} a_{kj} a_{ji}) A_o \ldots A_t A_M \Big)
\end{aligned}
\tag{24}
$$

The main steps of this methodology are as follows:

- Construct the digraph by considering criteria as nodes. The edges and their directions will be decided based on the interrelations among the criteria (a_{ij}*'s*).
- Determine the permanent matrix for the digraph which is one-to-one representation, in which diagonal elements represent the contribution of criteria and the off diagonal elements represent the relative importance among the criteria.
- Obtain the evaluation function for the matrix using equation (24). Substitute the values of A_i and a_{ij}, obtained in step 1, in equation (24) to evaluate the evaluation index.
- Calculate the numerical indices by substituting the value of attributes and their relative importance in the permanent function.
- The risk having the highest values of evaluation index is treated with top most priority.

The methodology presented in this work structure the problems related to the various risk options in reverse logistics. The hybrid MCDM methods can provide the decision maker a more realistic and accurate representation of the risk prioritization in reverse logistics.

5. Application of the hybrid MCDM methods: A case study

A real-world case problem is chosen to illustrate the application of the proposed approach**.** Worldwide around 8 million tons of PET waste is collected every year. This yields 5.9 million tons of flakes. India has a significant growth in the consumption of plastic items. In spite of this, the reverse logistics concept is not yet accepted. The company chosen for this research is a famous PET bottle recycling company situated in a state in the southern part of

India. The company has three recycling plants located at different cities of the state. The collected PET bottles are sorted and separated. The sorted post-consumer PET waste is crushed and pressed into bales. Further, it is subjected to crushing, washing, separating and drying. The regenerated polyester fibre is used in the textile industry, mainly in synthetic yarn spinning mills. The flakes are widely used for the manufacturing of different kinds of plastic items, and a variety of useful products such as carpet fibre, molding compounds. The industry collects the used products through third party reverse logistics provider (3PRLP). The recycled products have a wider acceptance in the market and it is planning to expand the business. Historically, the industry has obtained high level of profits, which started to decline. Considering this, the top level management wants to prioritize the risks in reverse logistics. Since one attribute dominates the other, the industry finds it difficult to evaluate the risk.

5.1 Analytic Hierarchy Process

5.1.1 Model the problem as a hierarchy

There are three levels in the hierarchy. The goal is at the topmost level of the hierarchy. The goal is to prioritise the reverse logistics risk. The second level characterizes the criteria. The required criteria are identified through the results of the questions. The criteria identified by the decision teams are given in Table 3. The third level represents the alternatives. The decision hierarchy is shown in Fig.2.

‘‘Insert Figure 2 here’’

After discussion with the company personnel, the pair wise comparison matrix is constructed starting from the lowest level of the hierarchy and shown in Table 6.

‘‘Insert Table 6 here’’

The criteria are compared pairwise with reference to the specified criteria in the higher level. The verbal judgements are then transformed into numerical values based on Satty's 9 point scale given in Table 4.

5.1.2 Test the consistency by evaluating the eigen vectors

The consistency check is implemented to ensure that the pairwise comparison matrix judgements are neither random nor illogical. The consistency ratio (CR) of a pairwise comparison matrix is calculated using Eq. 1 and Eq. 2. The CR obtained is shown in Table 7.

''Insert Table 7 here''

Since the calculated consistency ratio is less than 0.1, the matrix is accepted; the weights are consistent and can be used for the evaluation process.

AHP is used to determine the weight of the criteria that will be employed in fuzzy TOPSIS, PROMETHEE and digraph method. Since AHP derive scale from the discrete and continuous paired comparisons in multi-level hierarchical structures, it can be combined with other decision support techniques.

5.2 Integrating uncertainty in multi-criteria decision making process

In general, the nature of decision making process is usually complex. Some of the decision-making data is undefined, vague and fuzzy data. Uncertainties may be caused by human, machine or systems related issues. Good decision-making models should be able to tolerate vagueness or ambiguity. Human judgments including preference and experience are often vague; the decision maker estimates them with his intuition. In addition, decision makers may very well be reluctant or unable to assign crucial numerical values to compare judgments. Fuzzy logic is a method developed to incorporate uncertainty into a decision model which allows for including imperfect information. Fuzzy tools have shown to perform better than other soft approaches to decision making under uncertainties. This characteristic, including the ability to assign intermediate values between expressions offers a robust framework for model designers dealing with systems that contain high uncertainty. Table 8 represents the selection attribute on a qualitative scale using fuzzy logic, corresponding to the fuzzy conversion scale.

‘‘Insert Table 8 here’’

5.2.1 Hybrid AHP and Fuzzy TOPSIS

Fuzzy TOPSIS method is applied to aggregate the criteria and the alternative ratings to generate an overall score. For each alternative, the evaluation of the decision maker for various criteria are obtained in linguistic form (Excellent, Very high, High, Medium, Low, Very low). These linguistic values are converted into triangular fuzzy number using Table 4. The fuzzy decision matrix obtained for the nine alternatives is presented in Table 9. The fuzzy weighed decision matrix is constructed using Eq.11. Table 10 shows fuzzy weighed decision matrix.

‘‘Insert Tables 9 and 10 here’’

The range of triangular fuzzy numbers belongs to the closed interval (0, 1).Fuzzy positive-ideal solution and the fuzzy negative-ideal solution are defined as (1,1,1), (0,0,0) for benefit criterion and (0,0,0), (1,1,1) for cost criterion. In this case, Business interruption value (BI), Price increase (PI) and Business recovery time (BR) are cost criteria whereas the other criteria are benefit criteria. The distance of each alternative from positive and negative ideal solution is calculated using equations 14 and 15.

For the purpose of illustration, the computation of the closeness coefficient for environmental risk (A1) is described as follows:

The closeness coefficient for environmental risk (A1),

$$CC_1 = \frac{D_1^-}{D_1^+ + D_1^-} = \frac{3.5221}{3.5221 + 0.8902} = 0.4387$$

Similar calculations are done for the other alternatives and the results of AHP- fuzzy TOPSIS are summarized in Table 11.

‘‘Insert Table 11 here’’

The best alternative is the one with the greatest relative closeness to the ideal solution. Table 12 shows the ranking of the risks involved in reverse logistics. Based on the analysis of the results for the case company, managing inventory (A2) involves maximum amount of risk.

‘‘Insert Table 12 here’’

5.2.2 Sensitivity Analysis

Sensitivity analysis is done to determine the effect of criteria weights on decision making process. The analysis creates different scenarios that may change the precedence of alternatives. If the ranking order be changed by increasing or decreasing the importance of the criteria, the result is expressed to be sensitive otherwise it is robust. This is useful in situations where uncertainties exist in the definition of the importance of different factors. The main goal of sensitivity analysis is to see which criteria is most significant in influencing the decision making process. To find out the impact of weights on the risk prioritization, we conducted 28 experiments. Sensitivity analysis was conducted to exchange each criterion weight with another so that 28 different calculations can be done. CCj values for each calculation are done and different names are given for each calculation. For example, CC12 means criterion 1 and criterion 2 weights have changed and CC34 means criterion 3 and criterion 4 weights have changed. The details of the experiments are presented in Fig.3 and Fig.4.

‘‘Insert Fig. 3. here’’

‘‘Insert Fig. 4. here’’

It can be seen that A2 has the highest score in 26 experiments; A1 has the highest score in 2 experiments. It can be concluded that the decision making process is rarely sensitive to the criteria weights.

5.2.2 Hybrid AHP and PROMETHEE Method

For final evaluation, the weights obtained from AHP are utilized. After calculating the weights of the criteria using AHP method, the next step is to have the information on the decision maker’s preference function, which he/she uses when comparing the contribution of the alternatives in terms of each separate criterion. If two alternatives have a difference $d \neq 0$, the better alternative is assigned the value 1 while the worst alternative is given the value 0. If d =0, then they are indifferent which results in an assignment of 0 to both alternatives. Table 13 indicates the preference values for the criterion BI. Similarly preference values for the remaining criteria are obtained.

‘‘Insert Table 13 here’’

The weighed average of the preference functions is calculated using equation 19. For example, the weighed average of the preference function A1 with respect to A2 is obtained as follows:

$$\prod_{A1,A2} = \sum_{i=1}^{8} w_i P_{iA1,A2}$$

The criteria weights w_i are those obtained from AHP.

$$\prod_{A1,A2} =$$

$$= (0.0378)(0) + (0.0983)(0) + (0.0681)(0) + (0.2515)(0) + (0.1579)(0) + (0.0869)(0) + (0.1615)(0) + (0.1375)(0)$$

$$= 0$$

Similarly the weighed averages of the preference function for all the type of risk are obtained. Using equations 20-22, the leaving flow, entering flow, and the net flow are calculated.

For environmental risk (A1), the leaving flow is calculated as

$$\varphi^{+}(b) = \sum_{x \in B} \prod_{xb}$$

$$= 0.000 + 0.708 + 0.912 + 0.844 + 0.841 + 0.494 + 0.652 + 0.503$$

$$= 4.957$$

For environmental risk (A1), the entering flow is calculated as

$$\varphi^{-}(b) = \sum_{x \in B} \prod_{bx}$$

$$= 0.251 + 0.000 + 0.000 + 0.000 + 0.000 + 0.199 + 0.248 + 0.124$$

= 0.572

For environmental risk (A1), the net flow is calculated as

$$\varphi\ (b) = \varphi^{+}(b) - \varphi^{-}(b)$$

$$= 4.957 - 0.572$$

$$= 4.401$$

Similarly, the leaving flow, entering flow and the net flow values for different alternatives are calculated using equations 20–22 and the resulting preference indices are given in Table 14. From Table 15, inventory risk is considered as a major risk in reverse logistics network since it has the higher value of net flow.

‘‘Insert Table 14 here’’

‘‘Insert Table 15 here’’

5.3 Validation of the risk prioritisation using hybrid AHP-digraph and matrix method

Digraph and matrix method are applied to validate the results obtained from the previous two methods. The digraph for the case problem is presented in Fig.5.

‘‘Insert Figure 5 here’’

The values of the risk prioritisation evaluation function are based on the decision maker’s preference for the alternative using linguistic terms. These values are shown in Table 16. The quantitative values of the prioritisation attributes which are given in Table 16 are to be normalized. The attributes BI, PI and BR are non-beneficial attributes and lower values are desirable. The remaining attributes are beneficial attributes and higher values are preferred. The values corresponding to different attributes are normalized and are shown in Table 17.

‘‘Insert Table 16 here’’

‘‘Insert Table 17 here’’

The values of permanent function are determined and presented in Table 18.

‘‘Insert Table 18 here’’

From the above values of risk prioritisation index, it is understood that inventory risk is prioritised as the serious one and should be treated with care. Figures 6-8 show the comparison of the results obtained for the three hybrid methods of reverse logistics risk prioritisation. It is evident from figures 6, 7 and 8 that all the three methods provide the same ranking for the types of risks such as Inventory risk, Environmental risk, Disruption risk Quantity risk and Outsourcing risk. These five types of risks are serious risks and needs to be mitigated.

‘‘Insert Figure 6, 7 and 8 here’’

6. MANAGERIAL IMPLICATIONS

Due to the lack of knowledge on reverse logistics, many companies are not capable of or are unwilling to enter the reverse logistics market. But the companies cannot neglect the risk involved in reverse logistics. This paper proposes a methodology to evaluate the risks involved in reverse logistics. The managers can get an insight of these barriers and understand their relative importance along with their interdependencies. The proposed methodology acts as a guide to the top management to prioritise the risk in reverse logistics projects. This approach also enables the decision-makers to better understand the relationships of the relevant attributes in the decision-making, which may subsequently improve the reliability of the decision.

7. CONCLUSION

To the best of the knowledge of the authors, this study is the first study to direct attention towards the risks in reverse logistics. Impact of this risk can be minimized or even nullified. In order to maximise the profitability, risks involved in reverse logistics must be analysed. The findings in this paper will give them a better understanding of the relationship between the various functions involved in RL. The strength of this method is that it can be used to help decision makers to make key decisions considering not only the economic benefits but also the environmental and societal benefits considering the vagueness of experts' opinions. The methodology proposed identifies the hierarchy of actions to be taken for handling different risks hindering the implementation of reverse logistics. In addition, it is possible to vary the weights given to attributes so that priorities for attributes can be varied at any point. The present paper is also relevant for managers or policy makers who are carrying out RL operations. The findings of this work shows that the inventory risk is highly prioritized, and focused greatly in order to increase the effectiveness of RL adoption.

Once the risks in reverse logistics are prioritised, the responsiveness based risk mitigation strategies can be selected considering the risk- return trade- off. This study is important as it sheds lights on the risk perception of plastic recycling industry considering the potential risk factors. The results show that better performance in green practices is achieved by considering risks. This work bridges a gap on the lack of research that provides a solid understanding, review of risks involved in RL.

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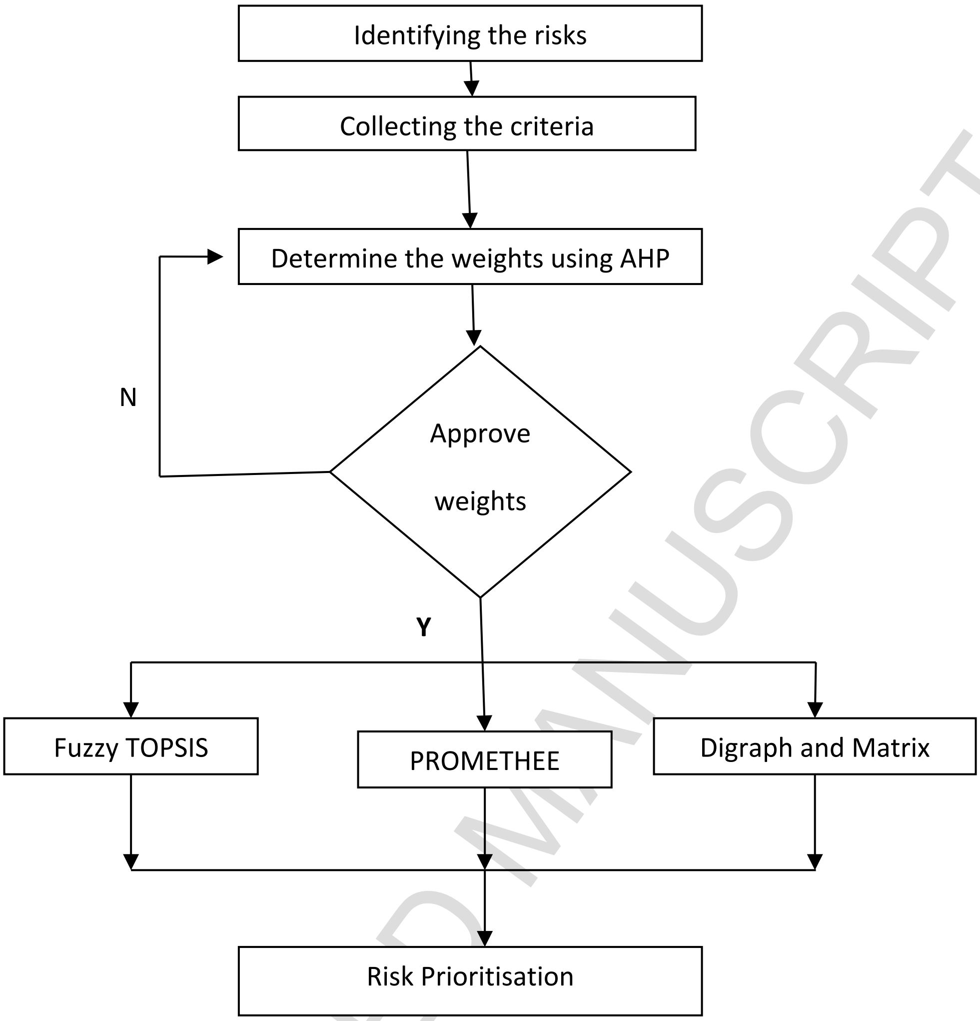

Fig.1. Methodology Adopted for RL risk prioritisation

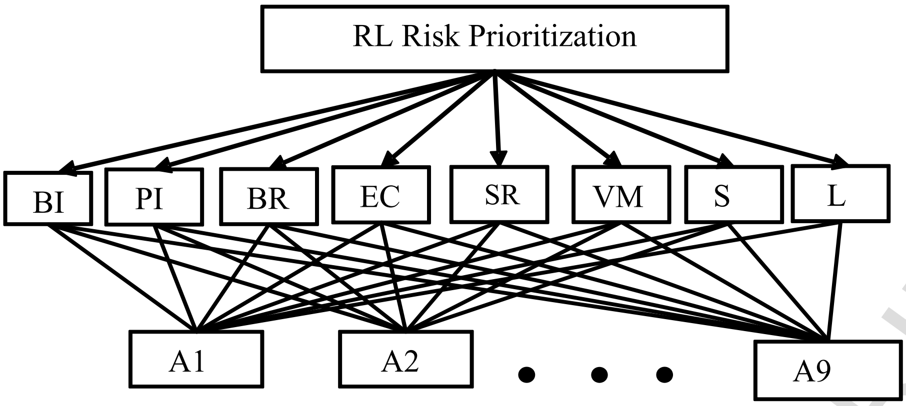

Fig. 2 Hierarchy for reverse logistics risk prioritisation

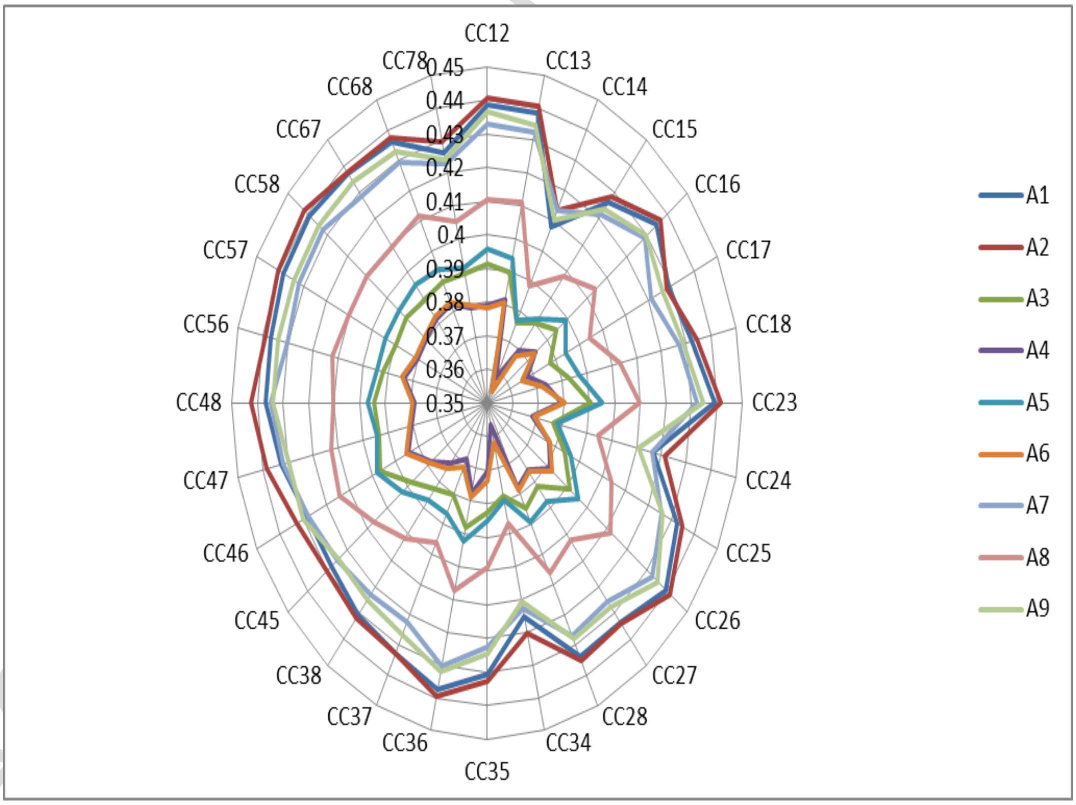

Fig.3. Sensitivity Analysis in Radar Chart

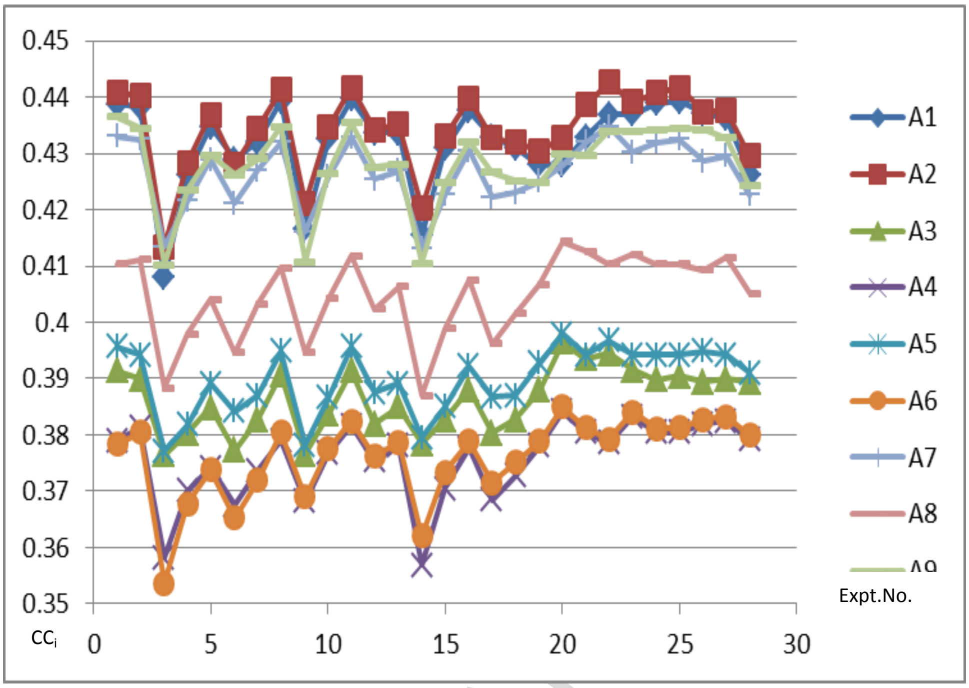

Fig. 4 Results of Sensitivity Analysis

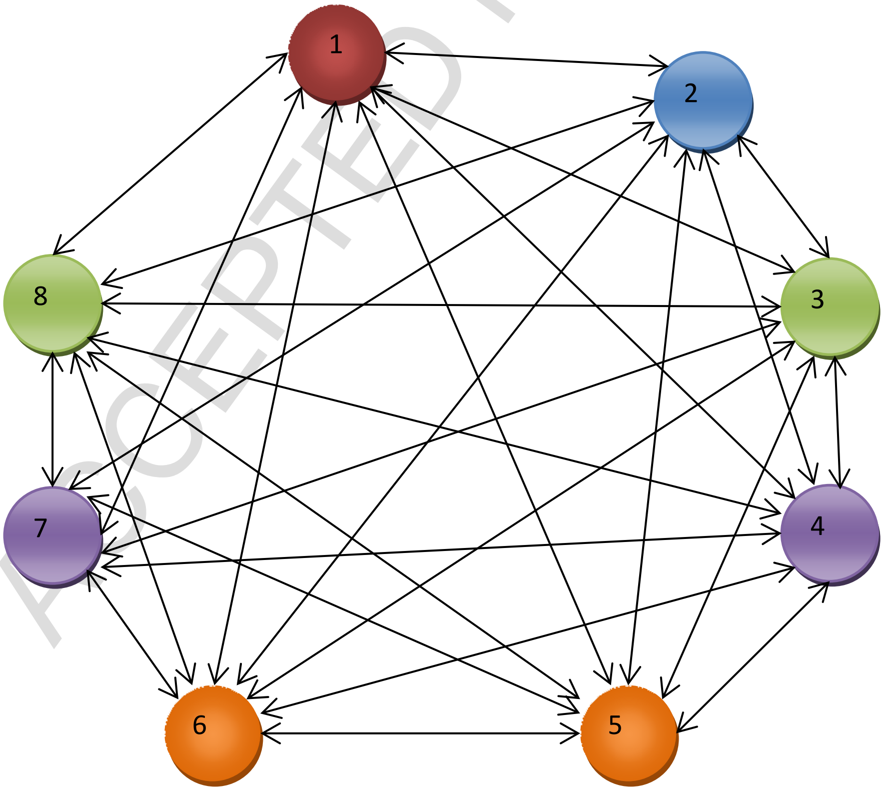

Fig. 5 Risk prioritisation digraph

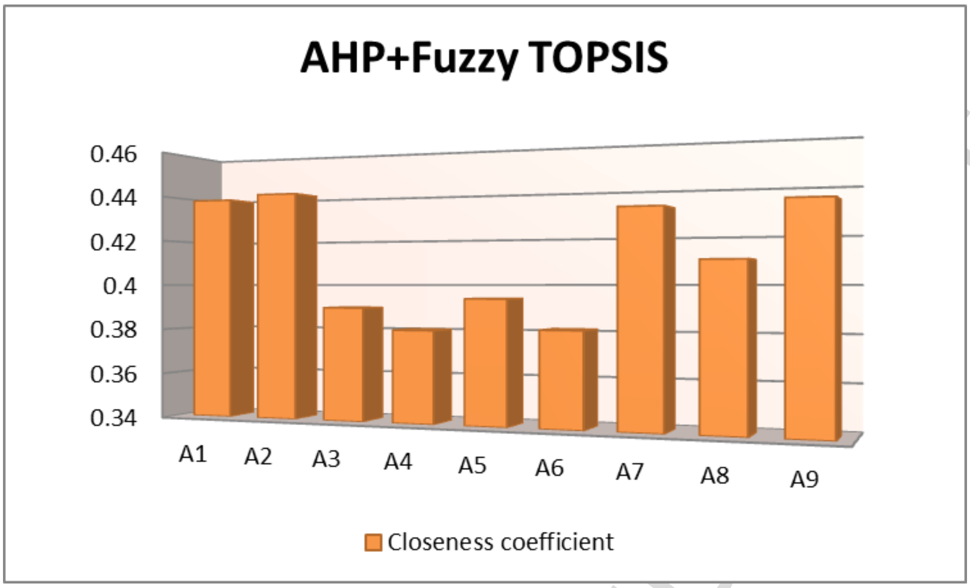

Fig. 6 Closeness coefficient using Hybrid AHP-Fuzzy TOPSIS

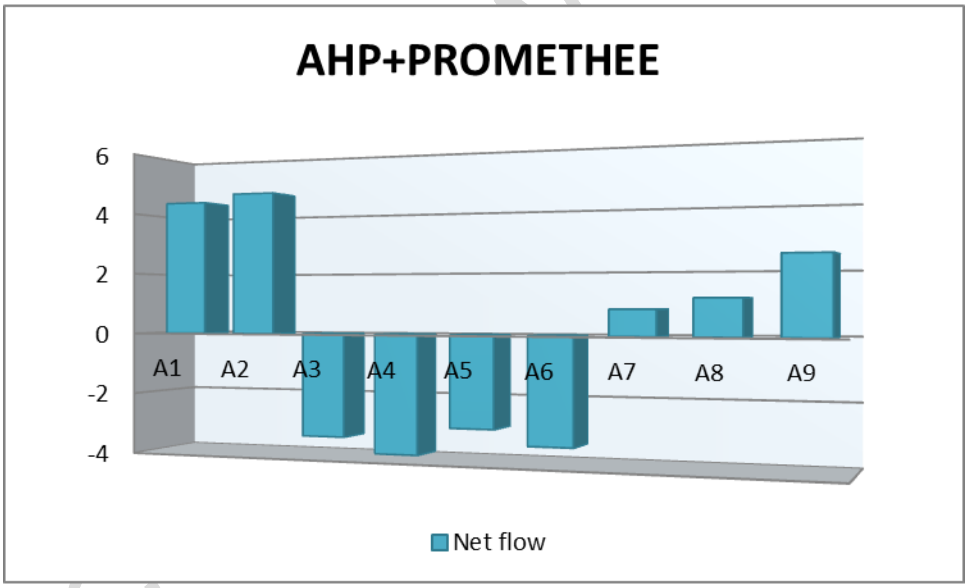

Fig. 7 Netflow obtained using Hybrid AHP-PROMETHEE

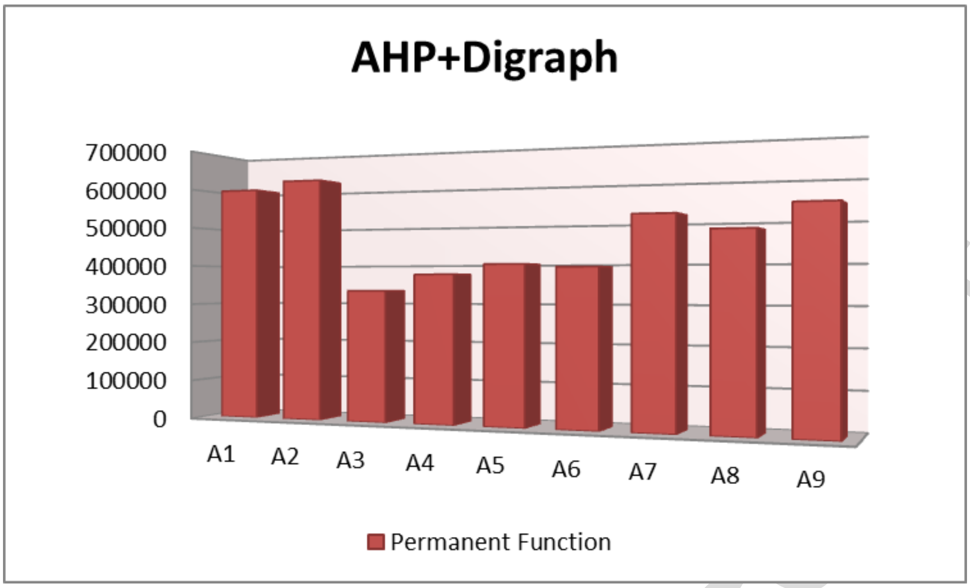

Fig. 8. Permanent function value obtained from Hybrid AHP-Digraph and Matrix

Table 1 Literature on risk management in forward logistics

References	Risk identification	Risk assessment	Risk prioritisation
Sheffi (2001)	√		
Van Landeghem and Vanmaele (2002)	√		
Juttner et al. (2003)	√		
Chopra and Sodhi (2004)	√		
Hallikas et al. (2004)	√	√	√
Norrman and Jansson (2004)	√	√	√
Shi (2004)	√	√	√
Zsidisin et al. (2004)		√	
Blackhurst et al. (2005)	√		
Juttner (2005)	√	√	√
Cucchiella and Gastaldi (2006)	√		
Gaudenzi and Borghesi (2006)		√	
Tang (2006)	√		
Wagner and Bode (2006)		√	
Khan and Burnes (2007)	√		
Ritchie and Brindley (2007)	√		
Klibi et al. (2010)	√		
Rao and Goldsby (2009)	√		
Vanany et al. (2009)	√	√	
Tuncel and Alpan (2010)		√	√
Tang and Nurmaya Musa (2011)	√		
Thun and Hoenig (2011)	√	√	√
Rajesh and Ravi (2015)	√		√
Lintukangas et al. (2016)	√		
Zhao et al,(2016)		√	

Table 2 Risks in reverse logistics

Sl. No	**Type of risk**	**Reference**
1	Environmental risk (A1)	Cucchiella and Gastaldi(2006), Oke and Gopalakrishnan (2009), Hsu and Hu (2009), Rajesh and Ravi (2015), Zho et al.(2016)
2	Inventory risk (A2)	Chopra and Sodhi (2004), Basu et al. (2007), Oke and Gopalakrishnan(2009)
3	Data managing risk (A3)	Chopra and Sodhi (2004), Norrman and Jansson (2004) and Tang (2006)
4	Time management risk (A4)	Finch (2004), Zho et al,(2016)
5	Managerial risk (A5)	Peck (2005), Rajesh and Ravi (2015)
6	Cultural risk (A6)	Rice and Caniato (2003)
7	Quantity risk (A7)	Van Landeghem and Vanmaele (2002), Shi (2004) and Cucchiella and Gastaldi(2006)
8	Outsourcing risks (A8)	Chopra and Sodhi (2012) , Lintukangas et al. (2016)
9	Disruption risk (A9)	Chopra and Sodhi (2012) ,Tang(2006),

Table 3 Prioritisation Criteria from Literature

Sl. No	Criterion	Reference
1	Business Interruption value (BI)	Van Landeghem and Vanmaele(2002), Rice and Caniato, (2003),Chopra and Sodhi (2004), Shi(2004), Zsidisin et al. (2004), Basu et al. (2007) and Thun and Hoenig(2011).
2	Price increase due to shortage of parts/fuel (PI)	Chopra and Sodhi (2004), Zsidisin et al. (2004) Shi (2004), Cucchiella and Gastaldi (2006) and Tang (2006)
3	Business recovery time after interruption (BR)	Norrman and Jansson (2004) , Blackhurst et al. (2005)
4	Environmental concern (EC)	Shi (2004) ,Sheffi (2007), Dowlatshahi (2005), Tan and Kumar (2006), Guide and Van Wassenhove (2009), Pokharel and Mutha (2009), Rahman and Subramanian(2012)
5	Social responsibility (SR)	Cucchiella and Gastaldi (2006)
6	Volume management (VM)	Carter and Ellram (1998), Knemeyer et al. (2002), Tibben-Lembke and Rogers (2002), Dowlatshahi (2005), Pokharel and Mutha (2009).
7	3PRLP service (S)	Liu and Wang(2009), Buyukozkan and Gifci (2012)
8	Legislation (L)	Carter and Ellram (1998), Knemeyer et al.(2002), Dowlatshahi (2005), Tan and Kumar(2006)

Table 4 Scale of Preference

Preference weights	Definition	Explanation
1	Equally preferred	Two attributes contribute equally
3	Moderately	Experience and judgement slightly favour one activity over another
5	Strongly	Experience and judgement strongly favour one activity over another
7	Very Strongly	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extremely	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate Values	When compromise is needed
Reciprocals	Reciprocals for Inverse comparison	

Source: Saaty (2000)

Table 5 Average random index values

Attributes	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.39	1.11	1.25	1.35	1.40	1.45	1.49

Source: Saaty (2000)

Table 6 Pairwise comparison matrix

Decision Criterion	BI	PI	BR	EC	SR	VM	S	L
BI	-	1/3	1/2	1/4	1/3	1/2	1/4	1/4
PI	3	-	2	1/4	2	1/3	1/3	1/2
BR	2	1/2	-	1/4	1/3	2	1/2	1/3
EC	4	4	4	-	1	3	3	2
SR	3	1/2	3	1	-	2	2	1
VM	2	3	1/2	1/3	1/2	-	1/3	1/2
S	4	3	2	1/3	1/2	3	-	2
L	4	2	3	1/2	1	2	1/2	-

Table 7 Consistency computations in AHP

Item	Value
Maximum. Eigen Value($\lambda_{\max}$)	8.9354
Consistency Index (CI)	0.1336
Random Index (RI)	1.40
Consistency Ratio (CR)	0.0954

Table 8 Linguistic terms and Fuzzy Numbers

Linguistic terms	Fuzzy Numbers
Very Low (VL)	(0.0, 0.0, 0.2)
Low (L)	(0.0, 0.2, 0.4)
Medium (M)	(0.2, 0.4, 0.6)
High (H)	(0.4, 0.6, 0.8)
Very High (VH)	(0.6, 0.8, 1.0)
Excellent (E)	(0.8, 1.0, 1.0)

Table 9 Fuzzy Evaluation Matrix

Type of risks	Decision Criterion							
	BI	PI	BR	EC	SR	VM	S	L
A1	Low (0.0,0.2,0.4)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)	Excellent (0.8,1.0,1.0)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)	Very High (0.6,0.8,1.0)
A2	Low (0.0,0.2,0.4)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)	Very High (0.6,0.8,1.0)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	Excellent (0.8,1.0,1.0)
A3	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Very Low (0.0,0.0,0.2)	Low (0.0,0.2,0.4)	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)
A4	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Very High (0.6,0.8,1.0)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)	Medium (0.2,0.4,0.6)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)
A5	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Low (0.0,0.2,0.4)	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)	Low (0.0,0.2,0.4)	Medium (0.2,0.4,0.6)
A6	Very High (0.6,0.8,1.0)	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)	Medium (0.2,0.4,0.6)	Low (0.0,0.2,0.4)	Very Low (0.0,0.0,0.2)
A7	Very Low (0.0,0.0,0.2)	Low (0.0,0.2,0.4)	Low (0.0,0.2,0.4)	High (0,4,0.6,0.8)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	High (0,4,0.6,0.8)
A8	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Medium (0.2,0.4,0.6)	High (0,4,0.6,0.8)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)
A9	Very Low (0.0,0.0,0.2)	Medium (0.2,0.4,0.6)	Low (0,0.2,0.4)	Very High (0.6,0.8,1.0)	High (0,4,0.6,0.8)	High (0,4,0.6,0.8)	Medium (0.2,0.4,0.6)	Very High (0.6,0.8,1.0)
Weights	0.0378	0.034	0.2058	0.1621	0.1547	0.1549	0.1367	0.0616

Table 10 Weighed Fuzzy Evaluation Matrix for RL risk prioritisation

Type of risk	BI	PI	BR	EC	SR	VM	S	L
A1	(0.00000, 0.00756, 0.01512)	(0.00000, 0.01966, 0.03932)	(0.0823, 0.1234, 0.1646)	(0.03242, 0.06484, 0.09726)	(0.0000, 0.0000, 0.03094)	(0.0000, 0.0000, 0.03098)	(0.0000, 0.02734, 0.05468)	(0.0000, 0.0000, 0.01232)
A2	0.00000, 0.00756, 0.01512)	(0.00000, 0.01966, 0.03932)	(0.0412, 0.0823, 0.1234)	(0.03242, 0.06484, 0.09726)	(0.03094, 0.06188, 0.09282)	(0.03098, 0.06196, 0.09294)	(0.0000, 0.02734, 0.05468)	(0.0000, 0.0000, 0.01232)
A3	(0.00756, 0.01512, 0.02268)	(0.03932, 0.05898, 0.07864)	(0.1646, 0.2058, 0.2058)	(0.12968, 0.1621, 0.1621)	(0.06188, 0.09282, 0.12376)	(0.06196, 0.09294, 0.12392)	(0.10936, 0.1367, 0.1367)	(0.01232, 0.02464, 0.03696)
A4	(0.01512, 0.02268, 0.03024)	(0.01966, 0.03932, 0.05898)	(0.1235, 0.1646, 0.2058)	(0.06484, 0.09726, 0.12968)	(0.06188, 0.09282, 0.12376)	(0.03098, 0.06196, 0.09294)	(0.05468, 0.08202, 0.10936)	(0.01232, 0.02464, 0.03696)
A5	(0.00756, 0.01512, 0.02268)	(0.03932, 0.05898, 0.07864)	(0.08232, 0.12348, 0.16464)	(0.03242, 0.06484, 0.09726)	(0.06188, 0.09282, 0.12376)	(0.09294, 0.12392, 0.1549)	(0.02734, 0.05468, 0.08202)	(0.03696, 0.04928, 0.0616)
A6	(0.02268, 0.03024, 0.03780)	(0.01966, 0.03932, 0.05898)	(0.08232, 0.12348, 0.16464)	(0.0000, 0.03242, 0.06484)	(0.12376, 0.1547, 0.1547)	(0.09294, 0.12392, 0.1549)	(0.02734, 0.05468, 0.08202)	(0.03696, 0.04928, 0.0616)
A7	(0.00000, 0.00000, 0.00756)	(0.0068, 0.0136, 0.0204)	(0.0411, 0.08232, 0.12348)	(0.06484, 0.09726, 0.12968)	(0.12376, 0.1547, 0.1547)	(0.03098, 0.06196, 0.09294)	(0.08202, 0.10936, 0.1367)	(0.02464, 0.03696, 0.04928)
A8	(0.00756, 0.01512, 0.02268)	(0.0000, 0.0068, 0.0136)	(0.0411, 0.08232, 0.12348)	(0.06484, 0.09726, 0.12968)	(0.12376, 0.1547, 0.1547)	(0.03098, 0.06196, 0.09294)	(0.0000, 0.0000, 0.02734)	(0.03696, 0.04928, 0.0616)
A9	(0.00000, 0.00000, 0.00756)	(0.01966, 0.03932, 0.05898)	(0.00000, 0.01362, 0.02724)	(0.15090, 0.20121, 0.25151)	(0.06316, 0.09474, 0.12632)	(0.03476, 0.05214, 0.06952)	(0.0323, 0.0646, 0.0969)	(0.0825, 0.1100, 0.1375)

Table 11 Distances to Ideal Solution

Type of Risk	Positive Ideal solution D_J^+	Negative Ideal solution D_J^-	Closeness coefficient CC_j
A1	0.8902	3.5221	0.4387
A2	0.8717	3.5389	0.4408
A3	0.9452	3.1354	0.3899
A4	0.9909	3.0620	0.3804
A5	0.9452	3.1706	0.3941
A6	0.9909	3.0680	0.3812
A7	0.8902	3.4692	0.4319
A8	0.9452	3.2956	0.4103
A9	0.8902	3.4843	0.4340

Table 12 Ranking obtained from Hybrid AHP - Fuzzy TOPSIS

Type of Risk	Rank
A1	2
A2	1
A3	7
A4	9
A5	6
A6	8
A7	4
A8	5
A9	3

Table 13 Preference values from the pairwise comparison for the criterion- Business Interruption value (BI)

Type of Risk	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	-	0	1	1	1	1	0	1	0
A2	0	-	1	1	1	1	0	1	0
A3	0	0	-	1	0	1	0	0	0
A4	0	0	0	-	1	1	0	1	1
A5	0	0	0	0	-	0	0	0	0
A6	0	0	0	0	1	-	0	0	1
A7	1	1	1	0	1	`1	-	0	0
A8	0	0	0	0	0	1	1	-	0
A9	1	1	1	0	1	0	0	1	-

Table 14 Leaving flow, Entering flow and Netflow

Type of Risk	A1	A2	A3	A4	A5	A6	A7	A8	A9	ϕ^+	Net Flow
A1	-	0.0000	0.7084	0.9126	0.8445	0.8413	0.4949	0.6528	0.5032	4.9577	4.4010
A2	0.2515	-	0.6136	0.8445	0.9126	0.8445	0.7765	0.5709	0.4179	5.232	4.6596
A3	0.0000	0.0000	-	0.0000	0.1361	0.0378	0.2515	0.0378	0.2893	1.1023	-3.340
A4	0.0000	0.0000	0.0000	-	0.2296	0.2638	0.2515	0.0000	0.0000	1.3075	-3.835
A5	0.0000	0.0000	0.5469	0.3685	-	0.615	0.0000	0.0681	0.0000	1.5985	-2.938
A6	0.0000	0.0000	0.3498	0.0681	0.6150	-	0.0000	0.0983	0.2042	1.3354	-3.4228
A7	0.1993	0.1059	0.9126	0.4858	0.6136	0.7547	-	0.3498	0.2598	3.6815	0.8292
A8	0.2484	0.1615	0.8242	0.7259	0.1852	0.6956	0.4441	-	0.1615	3.4464	1.1738
A9	0.1247	0.0378	0.8380	0.4744	1.0000	0.7055	0.6338	0.4949	-	4.3091	2.4732
ϕ^-	0.5724	0.5567	5.1433	4.4424	4.5366	4.7582	2.8523	2.2726	1.8359		

Table 15 Ranking obtained from Hybrid AHP-PROMETHEE method

Type of Risk	Rank
A1	2
A2	1
A3	7
A4	9
A5	6
A6	8
A7	4
A8	5
A9	3

Table 16 Values of reverse logistics risk function

Type of Risk	Decision Criterion							
	BI	PI	BR	EC	SR	VM	S	L
A1	0.2	0.2	0.0	1.0	0.6	0.4	0.4	0.8
A2	0.2	0.2	0.0	0.6	0.6	0.4	0.6	1.0
A3	0.4	0.6	0.4	0.0	0.2	0.4	0.4	0.4
A4	0.6	0.4	0.8	0.2	0.0	0.4	0.2	0.0
A5	0.4	0.6	0.4	0.2	0.4	0.4	0.2	0.4
A6	0.8	0.4	0.6	0.2	0.0	0.4	0.2	0.0
A7	0.0	0.2	0.2	0.6	0.6	0.4	0.6	0.6
A8	0.4	0.4	0.6	0.4	0.4	0.6	0.6	0.4
A9	0.0	0.4	0.2	0.8	0.6	0.6	0.4	0.8

Table 17 Normalized evaluation matrix

Type of Risk	Decision Criterion							
	BI	PI	BR	EC	SR	VM	S	L
A1	0.2	1	0.0	1.0	1.0	0.6	0.6	0.8
A2	0.2	1	0.0	0.6	1.0	0.6	1.0	1.0
A3	0.4	3	0.4	0.0	0.3	0.6	0.6	0.4
A4	0.6	2	0.8	0.2	0.0	0.6	0.3	0.0
A5	0.4	3	0.4	0.2	0.6	0.6	0.3	0.4
A6	0.8	2	0.6	0.2	0.0	0.6	0.3	0.0
A7	0.0	1	0.2	0.6	1.0	0.6	1.0	0.6
A8	0.4	2	0.6	0.4	0.6	1.0	1.0	0.4
A9	0.0	2	0.2	0.8	1.0	1.0	0.6	0.8

Table 18 Permanent function and ranking

Type of Risk	Permanent Function Value	Rank
A1	600025.3	2
A2	621149.6	1
A3	334811.3	9
A4	376721.4	8
A5	401478.9	6
A6	394140.1	7
A7	518457.2	4
A8	480584.3	5
A9	538789.2	3