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A New Failure Mode and Effects Analysis (NFMEA) Approach for Supplier Selection in Risk Environment

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Supplier selection is a multi-criteria problem which involves both qualitative and quantitative factors. It is a complex, multi-person and group decision making process that can be improved by systematic and logical approaches to assess priorities based on the inputs of several people from different functional areas within the company. In this research work, the authors have shown how fuzzy analytic hierarchy process (F-AHP) can be effectively used with failure mode and effects analysis (FMEA) approach for selecting the best supplier in risk's environment. F-AHP is used to determine the relative weight of every criterion and FMEA is used to calculate the risk of every criterion and sub-criterion related to the supplier. Therefore, this research proposes a new failure mode and effects analysis (NFMEA) approach to select the best supplier from supply chain risk's environment.

Field of Research: Risk Management

1. Introduction

Supplier selection can be defined as the process of finding the right suppliers. Manufacturers spend more than 60% of its total sales on purchased items (Krajewsld et al 1996).Therefore, selecting the right supplier significantly reduces purchasing costs, improves competitiveness in the market and enhances end user satisfaction (Onut et al 2009). Since supplier selection process mainly involves the evaluation of different criteria and various supplier attributes, so it can be considered as a multiple criteria decision making (MCDM) problem (Liao et al 2011). Dickson, the pioneer of supplier selection problem, identified 23 different criteria for selecting suppliers, including quality, delivery, performance history, warranties, price, technical capability, and financial position. With a thorough literature survey, (Weber et al 1991) reviewed 74 different articles by classifying into three categories; linear weighting methods, mathematical programming models, and statistical approaches. Boran et al (2009) identified four stages for supplier selection including; definition of the problem, formulation of criteria, qualification, and final selection respectively. Among different types of MCDM approaches, F-AHP approach is capable of handling the inherent subjectivity and ambiguity associated with the mapping of one's perception to an exact number. Hence, Buckley (1985) developed a fuzzy AHP model and following Buckley's work, various developments of Fuzzy AHP methods and applications have been carried out (Chen et al 2006). In any decision making process, decision criteria plays an important role. Because all the criteria associated with the decision making process do not have the same impact. So it is inevitable that the impact of decision criteria

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must be considered during the decision making process. If the impacts of decision making criteria are not considered, it would lead the decision maker to wrong path. But the existing research works do not give more importance on the impact of decision making criteria rather than it give more importance on the risk priority number of FMEA analysis which is illustrated in literature review. In conventional FMEA, the various sets of severity, detection and occurrence may produce the identical value of risk priority number and the risk implication may be totally different. So when there are several identical value of risk priority number of different criteria are produced, then it would be very difficult for the decision maker to take decision. This research work proposed weighted-RPN concept which successfully overcome this limitation. Multi-criteria decision making (MCDM) approaches only measure the relative weights of every alternatives and on the basis of the relative weights it take decision. To the best of the authors' knowledge, only FMEA and multi-criteria decision making process is not so effective for supplier selection in risk environment. In risk environment, risk associated with decision criteria and relative weight of decision criteria should be calculated. In this research work, the authors proposed a new Failure Mode and Effects Analysis (NFMEA) which integrate Fuzzy Analytic Hierarchy Process and FMEA approach. This propose NFMEA not only calculate the weights of decision criteria but also calculate their corresponding risks. To test the feasibility of our proposed NFMEA, the authors have done case study on supplier selection problem. In this study, the authors have considered six criteria: cost, quality, deliverability, organizational behaviour, environmental assessment and twenty six sub-criteria for supplier selection problem. The main objectives of this research work is to fill out the research gaps that are left out by other researchers.

This study arranged as follows- Part 2 presents the literature review to identify the research scope on supplier selection of risk environment. Part 3 explains the research methodology and the solution procedure. In this part, the F-AHP and FMEA methods are explained in detail which are utilized to solve the supplier selection of risk environment. Part 4 presents the summarized results of the study. Part 5 presents the conclusions of the study.

2. Literature Review

Generally, when a supplier selection decision needs to be made, the enterprise establishes a set of evaluation criteria that can be used to compare potential sources. In supplier selection decisions, two issues are very significant, first one is what criteria should be used, and the next one is what methods can be used to compare suppliers. Many studies have been performed for supplier selection by using different criteria starting from the Dickson's (1996) 23 criteria. Cheraghi et al (2004) updated Dickson's criteria with 13 more criteria. Quality, price, and delivery performances are suggested as the most important selection criteria for supplier selection (Liao et al 2011). Recently, it is observed that, various multi criteria decision making methods are implemented, which can be grouped into three broad categories (Wang et al 2011). These are:

1. Value Measurement Models: AHP and multi attribute utility theory (MAUT) are the best known method in this group.
2. Goal, Aspiration, and Reference Models: Goal programming and TOPSIS are the most important methods that belong to the group.

3. Outranking Methods: ELECTRE and PROMETHEE are two main families of methods in this group.

Zadeh (1965) developed the fuzzy set theory which can handle the impreciseness of human judgments. Fuzzy AHP method (Cheng 1997) systematically solves the selection problem that uses the concepts of fuzzy set theory and hierarchical structure analysis. Applications of F-AHP in various fields including; weapon selection (Dağdeviren et al 2009), energy alternatives selection (Kahraman et al 2010) and job selection (Kilic et al 2011).

Sellappan and Palanikumar (2013) modified prioritization methodology for risk priority number in failure mode and effects analysis. In this research paper the authors stated some limitations of the conventional risk priority number. This research work have shown the various sets of severity, detection and occurrence may produce the identical value of risk priority number and the risk implication may be totally different. The authors overcome this limitation of the conventional prioritization methodology for RPN in FMEA approach by using Multiple Regression Analysis.

Sachdeva et al (2009) used Failure mode effect and criticality analysis (FMECA) for maintenance problem. In this research work, the authors stated that FMECA does not consider the interdependence among the various failure modes and effects. They also mentioned that the assumption that the scales of three indexes; severity (S), occurrence (O) and detection (D) have the same metric and that the same design level corresponds to the same values on different index scales. The authors have used the concept of Shannon's entropy to assign objective weights to maintenance parameters and TOPSIS (technique for order preference by similarity to ideal solution) method to determine the Maintenance Criticality Index (MCI) to overcome the limitations of the conventional RPN.

Wang et al (2009) used Fuzzy Risk Priority Numbers (FRPNs) to overcome the limitation of the conventional RPN. The authors then used fuzzy geometric means to weigh the fuzzy ratings for Occurrence (O), Severity (S) and Detection (D), computed using alpha-level-sets and linear programming models. The FRPNs are then defuzzified using centroid defuzzification method, in which a new centroid defuzzification formula based on alphalevel sets was derived.

Sankar and Prabhu (2001) proposed modified FMEA approach to prioritize failures in a system FMEA to carry out corrective actions. The authors introduced a new Risk Priority Rank (RPR) technique. This technique utilizes a ranking scale of 1 to 1000 to represent the increasing risk of S, O and D combinations. They also stated that FMEA attempts to quantify risk without adequately quantifying the factors that contribute to risk. Hence, the risk priority number can be misleading.

Pillay and Wang (2003) proposed Evidential Reasoning (ER) using fuzzy rules base and grey relation theory to calculate the RPN number which overcome the drawbacks of the traditional FMEA approach. In this research work, the authors first established the relation between three risk factors S, O and D.

Seyed-Hosseini et al (2006) introduced the Decision Making Trial and Evaluation Laboratory (DEMATEL) for reprioritization of failure modes in FMEA approach. This is based on severity of effect or influence, and the direct and indirect relationships between them. The authors have shown that the DEMATEL method can be effectively used for analysing indirect relations. In this method it is possible to assign as many ranks to all alternatives and clustering alternatives in large systems.

Arabzad and Ghorbani (2011) integrated FMEA and DEA approach to classify purchasing items. In this method, weights of evaluation criteria are determined by FMEA techniques with fuzzy RPN numbers. Then the DEA technique is used to classify purchasing items considering supply risk and profit impact based on Kraljic's model.

Chen (2007) evaluated interdependence of corrective action by Interpretive Structural Model (ISM). Author then calculated the weight of a corrective action through the analytic network process (ANP) and then successfully combined the utility of corrective actions to make a decision on improvement priority order of FMEA using Utility Priority Number (UPN).

Bowles and Peláez (1995) proposed a new technique based on fuzzy logic for prioritization of failures for corrective actions in a Failure Mode Effects and Criticality Analysis (FMECA). The authors represented S, O and D as members of fuzzy sets to assess the failure risk in a FMECA. Then it is finally defuzzified by the weighted mean of maximum method to assess the riskiness of the failure.

In any decision making problem, all the criteria associated with it do not have the same impact. The decision criteria have great impact on decision making system. But from the through literature review, it is found that the researchers try to prioritize the conventional risk priority number in failure mode and effects analysis in an efficient way. Only a few number of researchers focus on the relative weights of the decision criteria. But the methods they use to calculate the relative weights are not so efficient. Because it does not consider the impreciseness of human judgements. In any decision making system impreciseness of human judgements play a very important role. So during the calculation of the weight of the decision criteria it is very important to consider impreciseness of human judgements. So our proposed methodology focused not only the prioritization system of the RPN of failure modes but also consider the interdependencies among various criteria and focus on their relative weights by considering the impreciseness of the human judgements.

3. Methodology

In the process of supplier selections, the decision criteria associated with the decision making system needs to be considered. Then the potential failure modes needs to be identified. To conduct this research work in an effective way, following steps are followed:

Step 3.1. Determining criteria for supplier selections
Step 3.2. Conducting the NFMEA method:
Step 3.2.1. Defining a scoring system for the supplier selection
Step 3.2.2. Identifying the potential failure modes
Step 3.2.3. Evaluating the impact of a failure mode and justifying its severity. The scales for severity are attached in Appendix A1.
Step 3.2.4.Determining factors that cause to failures and classifying the probability of occurrence of the failure. The scales for occurrence are attached in Appendix A2.
Step 3.2.5. Delineating the detection of each failure and scoring each sub-criteria. Following scales are used for detection:

Table 1: Detection Scales of Criteria

Detection	Rating	Probability of detection(%) for all criteria
Remote	1	76-100
Low	2	51-75
Moderate	3	26-50
High	4	0-25

Step 3.2.6. Weighting each criterion based on its importance: We have used Fuzzy analytic hierarchy process to determine the relative weights of each criterion.

3.1 Fuzzy Analytic Hierarchy Process

Fuzzy Analytic Hierarchy Process (F-AHP) embeds the fuzzy theory to basic Analytic Hierarchy Process (AHP). It takes the pair-wise comparisons of different alternatives with respective to various criteria that are performed through the linguistic variables, which are represented by triangular numbers and provides a decision support tool for multi criteria decision problems. F-AHP uses the following steps:

Step 3.1.1.Decision Maker compares the criteria or alternatives via linguistic terms shown in Table 2

Table 2: Linguistic Terms and the Corresponding Triangular Fuzzy Numbers

Saaty Scale	Definition	Fuzzy triangular Scale
1	Equal important	(1,1,1)
3	Weakly important	(2,3,4)
5	Fairly important	(4,5,6)
7	Strongly important	(6,7,8)
9	Absolutely important	(9,9,9)
2	The intermittent values between two adjacent scales	(1,2,3)
4		(3,4,5)
6		(5,6,7)
8		(7,8,9)

Step 3.1.2. If there is more than one decision maker, preferences of each decision maker ($\widetilde{d_{ij}^{k}}$) are averaged and ($\widetilde{d_{ij}}$) is calculated as follows:

$$\widetilde{d_{ij}^{k}} = \frac{\sum_{k=1}^{K} \widetilde{d_{ij}^{k}}}{K}$$

Step 3.1.3. According to averaged preferences, pair wise contribution matrices is updated as follows:

$$A = \begin{bmatrix} \widetilde{d_{11}} & \cdots & \widetilde{d_{1n}} \\ \vdots & \ddots & \vdots \\ \widetilde{d_{n1}} & \cdots & \widetilde{d_{nn}} \end{bmatrix}$$

Step 3.1.4. The geometric mean of fuzzy comparison values of each criterion is calculated as follows:

$$\tilde{r_i} = \left(\prod_{j=1}^{n} \widetilde{d_{ij}}\right)^{1/n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where, i= 1, 2, 3,…….n

and $\tilde{r_i}$ represents triangular values.

Step 3.1.5. The fuzzy weights of each criterion can be found with by incorporating next three steps.
Step 3.1.5.1. Find the vector summation of each $\tilde{r_i}$
Step 3.1.5.2.Find the (-1) power of summation vector. Replace the fuzzy triangular number, to make it in an increasing order.
Step 3.1.5.3.To finds the fuzzy weight of criterion i ($\widetilde{w_i}$), multiply each $\tilde{r_i}$ with this reverse vector.

$$\widetilde{w_i} = \tilde{r_i} \times (\tilde{r_1} + \tilde{r_2} + \cdots + \tilde{r_n})^{-1}$$

$$= (lw_i, mw_i, uw_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Since w_i are still fuzzy triangular numbers, it is de-fuzzified by using the following equation:

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

M_i is a non- fuzzy number. It is normalized by using following equation:

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Step 3.1.6. Calculating the RPN by FMEA

3.2 Failure Mode and Effects Analysis

It is a proactive tool, technique and quality method that enables the identification and prevention of process or product errors before they occur. In FMEA, the Risk Priority Number (RPN) is defined as follows:

Risk Priority Number (RPN), R= S×O×D ……………………………………..... (5)

Where, “S” is called the Severity, which may be defined as an assessment of how serious the effect of the potential failure mode is on the customer. “O” is called the probability of Occurrence, which may be defined as an assessment of the likelihood that a particular cause will happen and result in the failure mode during the intended life of the product. “D” is called the Detection, which may be defined as the assessment of the likelihood that the current controls will detect the cause of the failure mode. This can be defined also as the likelihood that the defect will reach the customer.

Step 3.2.1. Sorting each criterion by its RPNs
Step 3.3. Categorizing qualified suppliers

3.3 Problem Structure & Solution

The mathematical illustration of supplier selection in risk environment is given below:
The decision criteria are marked as following-

C_1 – Cost
C_2 – Quality
C_3 – Deliverability
C_4 – Productivity
C_5 – Organizational Behaviour
C_6 - Environmental Assessment

Now, the pairwise comparison matrice for decision criteria is presented as follows:

Table 3: Pairwise Comparison Matrice of Decision Criteria

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	(1,1,1)	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	(1,2,3)	(4,5,6)	(3,4,5)	(2,3,4)
C_2	(2,3,4)	(1,1,1)	(5,6,7)	(9,9,9)	(7,8,9)	(9,9,9)
C_3	$(\frac{1}{3},\frac{1}{2},1)$	$(\frac{1}{7},\frac{1}{6},\frac{1}{5})$	(1,1,1)	(2,3,4)	(1,2,3)	(1,2,3)
C_4	$(\frac{1}{6},\frac{1}{5},\frac{1}{4})$	$(\frac{1}{9},\frac{1}{9},\frac{1}{9})$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	(1,1,1)	(1,1,1)	$(\frac{1}{3},\frac{1}{2},1)$
C_5	$(\frac{1}{5},\frac{1}{4},\frac{1}{3})$	$(\frac{1}{9},\frac{1}{8},\frac{1}{7})$	$(\frac{1}{3},\frac{1}{2},1)$	(1,1,1)	(1,1,1)	$(\frac{1}{3},\frac{1}{2},1)$
C_6	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$	$(\frac{1}{9},\frac{1}{9},\frac{1}{9})$	$(\frac{1}{3},\frac{1}{2},1)$	(1,2,3)	(1,2,3)	(1,1,1)

The geometric means of fuzzy comparison values of the decision criteria are calculated by Eq.; for example the geometric means of the fuzzy comparison values of 'cost' criterion is calculated as Eq.(1)

$$\tilde{r_i} = \left(\prod_{j=1}^{n} d_{ij}\right)^{1/n}$$
$$= [(1*\frac{1}{4}*1*4*3*2)^{1/6}; (1*\frac{1}{3}*2*5*4*3)^{1/6}; (1*\frac{1}{2}*3*6*5*4)^{1/6}]$$
= [1.348006; 1.849311; 2.376177]

Hence, the geometric means of fuzzy comparison values of all decision criteria are shown in table 4.

Table 4: Geometric Means of Fuzzy Comparison Values of Decision Criteria

Criteria	$\tilde{r_i}$		
Cost	1.348006	1.849311	2.376177
Quality	4.222768	4.762203	5.227743
Deliverability	0.675774	1	1.389597
Productivity	0.339941	0.393344	0.49028
Organizational Behaviour	0.367641	0.445449	0.602047
Environmental Assessment	0.458243	0.648054	0.890899
Total	7.412374	9.098362	10.97674
Reverse(power of -1)	0.13491	0.10991	0.091102
Increasing order	0.091102	0.10991	0.13491

The fuzzy weight of 'cost' criterion is calculated by using Eq.(2) is shown below:

$\widetilde{w_i}$ = [(1.3448006*0.091102); (1.849311*0.10991); (2.376177*0.13491]
= [0.122806; 0.203258; 0.320569]

Hence the relative fuzzy weights of each decision criterion are given in Table 5

Table 5: Relative Fuzzy Weights of Each Decision Criterion

Criteria	$\widetilde{w_i}$		
Cost	0.122806	0.203258	0.320569
Quality	0.384701	0.523413	0.705272
Deliverability	0.061564	0.10991	0.18747
Productivity	0.030969	0.043232	0.066144
Organizational Behaviour	0.033493	0.048959	0.081222
Environmental Assessment	0.041747	0.071228	0.120191

The relative non-fuzzy weight of each criterion (Mi) is calculated by using the Eq.(3). The normalized weights (N_i) weights of each criterion is calculated by using the Eq.(4). Hence the averaged and normalized weights of each criterion is tabulated in table 6.

Table 6: Averaged and Normalized Weights of Decision Criterion

Criteria	Mi	N_i
Cost	0.215544	0.20488
Quality	0.537796	**0.511189**
Deliverability	0.119648	0.113729
Productivity	0.046782	0.044467
Organizational Behaviour	0.054558	0.051859
Environmental Assessment	0.077722	0.073876

In this case study, quality is the prime concern for the company. That's why, the decision maker give more importance on quality. Its relative weight is **0.511189** and cost is in the second position whose relative weight is **0.20488**

4. Summarized Results

Table 7: Synthesized Table of Weighted RPNs of Supplier A

Supplier A		Risk assessment					
Criterion	Sub criterion	S	O	D	RPN	sub-criterion's weight(Wi)	weight RPN (Ri)
Cost (0.20488)	Product's cost	2	2	1	4	0.09038	0.361518
	Inbound transportation cost	3	2	1	6	0.029472	0.176831
	Charge of support service	3	2	1	6	0.029472	0.176831
	Exchange rate	2	4	1	8	0.055557	0.444455
Quality (0.511189)	Input quality control	2	3	1	6	0.198583	**1.191499**
	Reliability	3	2	1	6	0.106223	0.637338
	Durability	2	4	1	8	0.106223	0.849784
	Defect rate	2	4	1	8	0.048825	0.390596
	Product line compliant rate	3	2	1	6	0.051335	0.308012
Deliverability (0.113729)	Production cycle	4	2	1	8	0.018158	0.145262
	On time livery	2	3	1	6	0.053747	0.322485
	Delivery lead time	3	2	1	6	0.008882	0.053291
	Idle rate	2	4	1	8	0.032942	0.263536
Productivity (0.044467)	Productivity flexibility	2	3	1	6	0.033012	0.198071
	Amount of production	3	3	1	9	0.011455	0.103099
Organizational behaviour (0.051859)	Responsiveness	4	2	1	8	0.010276	0.082205
	Claim policy	3	2	1	6	0.010276	0.061654
	Social responsibility	4	3	1	12	0.005791	0.069487
	Research & development	3	4	1	12	0.010276	0.123307
	Reputation	4	3	1	12	0.002656	0.031877
	Innovation	3	2	1	6	0.010276	0.061654
Environmental assessment (0.073876)	Energy consumption	4	2	1	8	0.016026	0.128208
	Green packaging	2	3	1	6	0.016026	0.096156
	Waste management	3	4	1	12	0.016026	0.192312
	Recyclable/reusable product	2	3	1	6	0.005413	0.032481
	Emission	2	2	1	4	0.016026	0.064104
						0.993332	6.566052
							1.094342

Note: "S" means Severity; "O" means Occurrence; and "D" means Detection
Risk Priority Number = S×O×D; Weight RPN (R_i) = Criterions weight (W_i) × RPN

The relative weight of decision criteria and sub-criteria are calculated by F-AHP method. The conventional FMEA only consider RPN to take decision. Here the highest RPN is 12. It occurs in several times. Similarly, other RPN also occurs in several times. When, this case happens, it is very difficult for the decision maker to take decision. This is the major limitation of conventional FMEA. To overcome this limitation, authors use the concept of weight-RPN. Here, the RPN is calculated with respect to the relative weight of decision criteria on decision making system. Now, the highest value of weight-RPN is **1.191499** which occurs only one time. Average weight-RPN of supplier A is 1.094342. Similarly, average weight-RPN of supplier B and supplier C are 0.782507 and 1.111918. Detail calculations of supplier B and supplier C are attached in Appendix (A3, A4). Hence, supplier B is the lowest weight-RPN, so the best supplier is supplier B.

5. Conclusions

In this study, we propose a modified failure mode and effects analysis (MFMEA) to select the best supplier in supply chain risk environment. When same value of RPN occurs for different decision criteria, then the conventional FMEA is incapable to deal with it. To overcome this limitation, researchers use fuzzy triangular number. But there is also a chance to occur same value of RPN. Fuzzy triangular number and other improvements of FMEA cannot fully overcome this limitation. But this propose method overcome the limitation of conventional failure mode and effects analysis (FMEA). In this research because of confidentiality the suppliers' exact names are hidden. None of the voters claim anything negative about the selection process and they were also very satisfied about the selection process. Despite the contributions, the study has still some limitations. The study is based on the information given by the suppliers. And the relative weight of every criterion may be changed when the case company will different. In this study, six criteria and twenty six sub criteria are considered, but it may not be sufficient for other company. Other than the F-AHP, the other multi-criteria decision making approach such as Fuzzy Analytic Network Process (ANP), Fuzzy TOPSIS etc. can also be used with FMEA. The authors also suggest to use Fault tree analysis, Delphi method or stress testing other than FMEA and to incorporate with MCDM approaches.

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Appendix 1

Severity Scales of Criteria

Severity	Rating	Descriptions
Remote	1	Cost: supplier offers cheap raw material Quality: supplier offer very few defects material Deliverability: supplier very rarely miss the on time delivery Productivity: supplier has a strong ability to manufacture raw materials for the company Organizational behaviour: supplier can handle the case company's complaint within very short time Environmental assessment: very little amount of emission of CO_2 , NO_x , SO_2 and dust
Low	2	Cost: supplier offers medium-priced raw material Quality: supplier offer small amount defects material Deliverability: supplier rarely miss the on time delivery Productivity: supplier has a normal ability to manufacture raw materials for the company Organizational behaviour: supplier can handle the case company's complaint within moderate time Environmental assessment: little amount of emission of CO_2 , NO_x , SO_2 and dust
Moderate	3	Cost: supplier offers high-priced raw material Quality: supplier offer many defects material Deliverability: supplier miss the on time delivery most of the time Productivity: supplier has low ability to manufacture raw materials for the company Organizational behaviour: supplier can handle the case company's complaint within long time Environmental assessment: : moderate amount of emission of CO_2 , NO_x , SO_2 and dust
High	4	Cost: supplier offers very expensive raw material Quality: supplier offer abundant defects material Deliverability: supplier always miss the on time delivery Productivity: supplier has very low ability to manufacture raw materials for the company Organizational behaviour: supplier can handle the case company's complaint within very long time Environmental assessment: : large amount of emission of CO_2 , NO_x , SO_2 and dust

Appendix 2

Occurrence Scales of Criteria

Occurrence	Rating	Descriptions
Remote	1	Cost: supplier rarely offers expensive raw materials Quality: supplier rarely offers defects material Deliverability: supplier very rarely miss the on time delivery Productivity: supplier rarely cannot manufacture raw materials for the company Organizational behaviour: supplier rarely fails to handle the case company's complaint Environmental assessment: supplier rarely emits CO_2 , NO_x , SO_2 and dust in a large scale
Low	2	Cost: supplier often offers expensive raw materials Quality: supplier sometimes offers defects material Deliverability: supplier rarely miss the on time delivery Productivity: supplier cannot sometimes manufacture raw materials for the company Organizational behaviour: supplier sometimes fails to handle the case company's complaint Environmental assessment: supplier sometimes emits CO_2 , NO_x , SO_2 and dust in a large scale
Moderate	3	Cost: supplier usually offers expensive raw materials Quality: supplier often offers many defects material Deliverability: supplier miss the on time delivery most of the time Productivity: supplier often cannot manufacture raw materials for the company Organizational behaviour: supplier fails to handle the case company's complaint most of the time Environmental assessment: supplier emits CO_2 , NO_x , SO_2 and dust most of the time in a large scale
High	4	Cost: supplier always offers expensive raw materials Quality: supplier offers abundant defects materials Deliverability: supplier always miss the on time delivery Productivity: supplier usually cannot manufacture raw materials for the company Organizational behaviour: supplier always fails to handle the case company's complaint Environmental assessment: supplier always emits CO_2 , NO_x , SO_2 and dust in a large scale

Appendix 3

Synthesized Table of Weighted RPNs of Supplier B

Supplier B		Risk assessment					
Criterion	Sub criterion	S	O	D	RPN	sub-criterion's weight(Wi)	weight RPN(Ri)
Cost	Product's cost	3	2	1	6	0.09038	0.542277
	Inbound transportation cost	2	3	1	6	0.029472	0.176831
	Charge of support service	2	2	1	4	0.029472	0.117887
	Exchange rate	3	1	1	3	0.055557	0.166671
Quality	Input quality control	1	2	1	2	0.198583	0.397166
	Reliability	2	3	1	6	0.106223	0.637338
	Durability	3	1	1	3	0.106223	0.318669
	Defect rate	3	2	1	6	0.048825	0.292947
	Product line compliant rate	2	3	1	6	0.051335	0.308012
Deliverability	Production cycle	3	2	1	6	0.018158	0.108947
	On time livery	1	3	1	3	0.053747	0.161242
	Delivery lead time	2	2	1	4	0.008882	0.035527
	Idle rate	3	4	1	12	0.032942	0.395303
Productivity	Productivity flexibility	2	2	1	4	0.033012	0.132047
	Amount of production	1	4	1	4	0.011455	0.045822
Organizational behaviour	Responsiveness	3	2	1	6	0.010276	0.061654
	Claim policy	2	4	1	8	0.010276	0.082205
	Social responsibility	3	1	1	3	0.005791	0.017372
	Research & development	3	3	1	9	0.010276	0.092481
	Reputation	3	2	1	6	0.002656	0.015938
	Innovation	3	4	1	12	0.010276	0.123307
Environmental assessment	Energy consumption	4	1	1	4	0.016026	0.064104
	Green packaging	2	4	1	8	0.016026	0.128208
	Waste management	4	2	1	8	0.016026	0.128208
	Recyclable/reusable product	3	3	1	9	0.005413	0.048721
	Emission	2	3	1	6	0.016026	0.096156
						0.993332	4.695041
							0.782507

Note: “S” means Severity; “O” means Occurrence; and “D” means Detection
Risk Priority Number = S×O×D; Weight RPN (R_i) = Criterions weight (W_i) × RPN

Appendix 4

Synthesized Table of Weighted RPNs of Supplier C

Supplier C		Risk assessment					
Criterion	Sub criterion	S	O	D	RPN	Sub-criterion's weight(Wi)	Weight RPN(Ri)
Cost	Product's cost	3	2	1	6	0.09038	0.542277
	Inbound transportation cost	2	3	1	6	0.029472	0.176831
	Charge of support service	2	2	1	4	0.029472	0.117887
	Exchange rate	3	4	1	12	0.055557	0.666683
Quality	Input quality control	2	2	1	4	0.198583	0.794333
	Reliability	3	3	1	9	0.106223	0.956007
	Durability	4	3	1	12	0.106223	1.274676
	Defect rate	2	2	1	4	0.048825	0.195298
	Product line compliant rate	3	1	1	3	0.051335	0.154006
Deliverability	Production cycle	3	2	1	6	0.018158	0.108947
	On time livery	2	1	1	2	0.053747	0.107495
	Delivery lead time	3	3	1	9	0.008882	0.079936
	Idle rate	3	2	1	6	0.032942	0.197652
Productivity	Productivity flexibility	4	2	1	8	0.033012	0.264095
	Amount of production	3	4	1	12	0.011455	0.137465
Organizational behaviour	Responsiveness	3	2	1	6	0.010276	0.061654
	Claim policy	3	3	1	9	0.010276	0.092481
	Social responsibility	4	2	1	8	0.005791	0.046325
	Research & development	2	4	1	8	0.010276	0.082205
	Reputation	2	3	1	6	0.002656	0.015938
	Innovation	3	4	1	12	0.010276	0.123307
Environmental assessment	Energy consumption	3	3	1	9	0.016026	0.144234
	Green packaging	3	2	1	6	0.016026	0.096156
	Waste management	3	2	1	6	0.016026	0.096156
	Recyclable/reusable product	4	2	1	8	0.005413	0.043308
	Emission	2	3	1	6	0.016026	0.096156
						0.993332	6.671506
							1.111918

Note: “S” means Severity; “O” means Occurrence; and “D” means Detection
Risk Priority Number = S×O×D; Weight RPN (R_i) = Criterions weight (W_i) × RPN